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EXPLORING THE USE OF SMART GLASSES, GESTURE CONTROL, AND ENVIRONMENTAL DATA IN AUGMENTED REALITY GAMES

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ABSTRACT

In the last decade, augmented reality has become a popular trend. Big corporations like Microsoft, Facebook, and Google started to invest in augmented reality because they saw the potential that it has especially with the rising of the consumer version of the head mounted displays such as Microsoft's HoloLens and the ODG's R7. However, there is a gap in the knowledge about the interaction with such devices since they are fairly new and an average consumer cannot yet afford them due to their relatively high prices.

In this thesis, the Ghost Hunters game is described. The game is a mobile augmented reality pervasive game that uses the environment light data to charge the in-game "goggles". The game has two different versions, a smartphone and smart glasses version. The Ghost Hunters game was implemented for exploring the use of two different types of interactions methods, buttons and natural hand gestures for both smartphones and smart glasses. In addition to that, the thesis sought to explore the use of ambient light in augmented reality games.

First, the thesis defines the essential concepts related to games and augmented reality based on the literature and then describes the current state of the art of pervasive games and smart glasses.

Second, both the design and implementation of the Ghost Hunters game are described in detail. Afterwards, the three rounds of field trials that were conducted to investigate the suitability of the two previously mentioned interaction methods are described and discussed.

The findings suggest that smart glasses are more immersive than smartphones in context of pervasive AR games. Moreover, prior AR experience has a significant positive impact on the immersion of smart glasses users. Similarly, males were more immersed in the game than females. Hand gestures were proven to be more usable than the buttons on both devices. However, the interaction method did not affect the game engagement at all, but surprisingly it did affect the way users perceive the UI with smart glasses. Users that used the physical buttons were more likely to notice the UI elements than the users who used the hand gestures.

Keywords: pervasive games, augmented reality, smart glasses, human-computer interaction, hand gestures interface, environmental data.

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FOREWORD

This thesis provides some insights on both the interaction techniques and the usage of environmental data in mobile pervasive games. As any project this thesis would not have seen the light without the help and assistant of some individuals.

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Oulu, October 27th, 2017

Mounib Mazouzi

ABBREVIATIONS

3D	Three Dimensional
AR	Augmented Reality
AV	Augmented Virtuality
AI	Artificial Intelligence
CES	Consumer Electronics Show
CPU	Central Processing Unit
FOV	Field Of View
HCI	Human Computer Interaction
HD	High Definition
HMD	Head Mounted Display
HMPD	Head Mounted Projection Display
HPU	Holographic Processing Unit
ID	Identifier/Identity
IDE	Integrated Development Environment
IMU	Inertia Measurement Unit
GB	Gigabytes
GEQ	Game Engagement Questionnaire
GPS	Global Positioning System
GPRS	General Packet Radio Service
GPU	Graphics Processing Unit
GNSS	Global Navigation Satellite System
GLONASS	Global'naya Navigatsionnaya Sputnikovaya Sistema
MR	Mixed Reality
MP	Mega Pixels
MUM	Mobile and Ubiquitous Multimedia
ODG	Osterhout Design Group
OST-HMD	Optical See-Through Head Mounted Display
OMAP	Open Multimedia Applications Platform
OS	Operating System
OST	Optical See-Through
PC	Personal Computer
PDA	Personal Digital Assistant
PSP	Play Station Portable
QR code	Quick Response Code
RAM	Random Access Memory
SDK	Software Development Kit
SLAM	Simultaneous Localization And Mapping
SOC	System on Chip
SUS	System Usability Scale
UI	User Interface
UX	User Experience
VE	Virtual Environment
VST-HMD	Video See Through Head Mounted Display
VR	Virtual Reality

1. INTRODUCTION

1.1. Background

Video games have become part of our daily life. Whether it is in our homes, our working places (even though it is a bad idea but we are still doing it) or even when we are traveling on a bus, train, or an airplane. Each of these places contains some information or data that is unique that we call environmental data. This data is used in context aware applications like Google Maps[1] that can tell where you are and based on that, it can trigger an event such as suggesting nearby restaurants, for instance. Using environmental data in applications is not something new. However, using them in games is not that common even in the academia. One thing that will make environmental data essential for the future video games is the rise of the new wearables, especially the smart glasses. These gadgets are more powerful than the average smartphones and can compete with tablets in terms of computational power. However, they are still not affordable by the average consumers. Since these devices are relatively new, the interaction with them is a potential field for research. The rise of the smart glasses made some companies invest in one of its potential uses, augmented reality (AR) which is a live, direct or indirect, view of a physical, real-world environment whose elements are augmented by computer-generated sensory input such as sound, video, graphics or GPS data.

The use of AR along with the environmental data in smart phone games was shown to be effective; games like Pokémon GO[2] and Ingress[3] were successful in terms of engagements and popularity (more than 10 million downloads). Both games use environmental data such as the location of the player and time of the device to trigger game events like changing the position of the player and the in-game world state to day or night.

1.2. Objective

This thesis aims to explore the usability of two different interaction techniques, the natural hand gestures and the buttons in mobile pervasive AR games for both smart phones and smart glasses. In addition, this thesis provides some insights about the potential use of the environmental data in such games.

1.3. Method and research questions

The use of hand gestures and buttons in two different devices is explored. Hence, the main research question that this thesis answers is "Which interaction method is more suitable for each device?". The hypothesis suggests that the hand gestures are more engaging and immersive since they are more natural. To prove or disprove the hypothesis, Ghost Hunters was developed, a mobile AR game that works on both smartphones

[1] https://play.google.com/store/apps/details?id=com.google.android.apps.maps
[2] https://play.google.com/store/apps/details?id=com.nianticlabs.pokemongo
[3] https://play.google.com/store/apps/details?id=com.nianticproject.ingress

and smart glasses. The game uses the traditional rock, paper, and scissors game as a metaphor for the interaction where users can capture ghosts by .The game has two different modes, the button mode where players uses either virtual button on the display, or a physical button from an external device to capture the ghosts. The other mode is the hand gesture mode in which players can use the paper, rock, and scissors hand gestures to capture the ghosts corresponding to the opposite gesture (for instance rock gesture to capture scissors ghost). This variation produced four different conditions that can be used to determine the effect of interaction techniques and devices used on both the usability of the game, and the engagement of players. The four different conditions which will be discussed more in section 6.1.2 are : smart glasses hand gestures (SGH), smart glasses buttons (SGB), smartphone hand gestures (SPH), and smartphone buttons (SPB). The second research question this thesis addresses is "whether is it beneficial to use environmental data in AR pervasive games or not". To answer this question users were asked about their opinion in a short semi-constructed interview. Field trials were used as an evaluation technique in which three field trials were conducted in a semi-controlled environment at different locations inside the University of Oulu campus, Finland. Altogether, 84 participants tried at least one of the four conditions and then gave their feedback. In the final field trial, a combination of two famous questionnaires, the System Usability Scale (SUS) [1] and Game Engagement Questionnaire (GEQ) [2] were used to measure the usability of the system and the engagement of the users. In addition to that, a short semi-constructed interview was conducted and recorded.

1.4. Contribution

This work will contribute to the Human-Computer Interaction (HCI) field by giving some new insights about the suitable interaction techniques for both smart glasses and smartphones in mobile AR games. In addition to that, this thesis will show how to integrate environmental data seamlessly in design of the pervasive games to create immersive experiences. The author of this thesis published a short paper in the MUM (Mobile and Ubiquitous Multimedia) 2016 conference [3], in which he described the initial prototype and the first field trial results. A manuscript is under preparation for a full paper in which findings from the final evaluation are encapsulated.

1.5. Thesis structure

In Chapter 2, the terms game and play are defined for a better understanding. Afterwards, a specific type of games which is more related to this thesis called pervasive games is defined and described in detail. Chapter 2 is concluded by defining two common terms, the augmented and virtual realities along with the concepts immersion and presence.

Chapter 3 explains the different realities that are, the virtual and "the real" realities and shows how the combination of these two realities interconnect in what is called mixed reality (MR) especially a subsection of it called AR. The chapter also defines the three core techniques and technologies used to create AR application, the tracking techniques, the interaction techniques, and the display techniques. It explains and describes how each of these techniques is done, what is its current state of the art, limitations, and expectations for the future. Afterwards certain smart glasses models are described in detail. Finally, the chapter is concluded with some guidelines from the state of the art for making better AR experiences.

Chapter 4 presents the current state of the art of pervasive games and their three generations, it defines these generations based on the literature and gives some examples from each generation. Moreover, the chapter describes some games from both the academia and the industry that use environmental data.

Chapter 5 describes the game Ghost Hunters that has been implemented for comparing different interaction techniques for mobile pervasive AR games run on smart glasses and smartphones. The chapter describes its concept and the design process. After that, it will move to the implementation where the system architecture is described.

Chapter 6 describes the three field trials that used to evaluate Ghost Hunters. The setup, the participants, and the data collected are all described in detail.

Chapter 7 showcase the findings obtained from the third field trial along with some statistical analysis to find correlations between the different data variables. Chapter 8 will discuss the results obtained, answer the research questions, and suggests ways for extending the work.

Finally, chapter 9 summarized and concludes the work done in this thesis.

2. DEFINITIONS

This chapter explains the different concepts used in the thesis. It first starts by explaining terms related to games and pervasive games and then it discusses AR related terms in more detail.

2.1. Games and play

Before one starts defining pervasive games, one should first define games. Schell, J, said in his famous book “The Art of Game Design: A book of lenses“ that ”a game is a problem solving activity, approached with a playful attitude”[4]. According to this definition, games consist of two elements, the first one is the problem solving activity that makes the player interested in the game and pushes him/her to continue playing. The second element is the playful attitude, and this is what distinguishes “work” and “games”, so when someone find the joy or the “fun element” in his/her work, he/she will not perceive that activity as work anymore, instead, he/she will see it as a game. Schell mentioned that fact in [4] by quoting a song from Marry Poppins movie called “a spoon full of sugar”: “In every job that must be done there is an element of fun you find the fun and snap! The job’s a game”.

2.2. Pervasive games

Deterding et al. mentioned in [5] that within the socio-cultural trend of ”Ludification”, there are at least three trajectories relating to video games and HCI: (1) the extension of games (pervasive games); (2) the use of games in non-game contexts; (3) and playful interaction. This definition suggests that pervasive games are the “extension of games”, but what does extending games mean and how can we achieve it? Luckily, Montola et al. answered this question in [6] where they said: “Pervasive game is a game that has one or more salient features that expand the contractual magic circle of play socially, spatially or temporally”. Therefore, the expansion that Deterding et al. [5] were talking about was in three different axes, the social axis, the spatial axis, and the temporal axis. Pervasive games are typically based on scenarios exploiting contextual information of the player’s environment hence they expand the gaming experiences out into the physical world (real world) [7][8]. Usually, pervasive games are highly immersive, edgy, controversial and life changing [9].

One category of pervasive games is mobile pervasive games. Valente et al.[10] describe mobile pervasive games in terms of three characteristics: (1) they are a subclass of pervasive games; (2) they are context-aware games; and (3) they use mobile devices. The first characteristic implies that mobile pervasive games should extend the gaming experience either socially, spatially, or temporally. The second characteristic indicates that these games are unpredicted by using content related to the real world. The third characteristic shows that the game should be portable and can be played anywhere. Hand-held devices and head mounted displays (HMD)s provide such portability since they are mobile and can be used anywhere. Moreover, one of the biggest trends in the

HMDs research are the optical see-through HMD (OST-HMD) which are mainly used for AR applications. These displays will be discussed more in Section 3.3.1.

2.3. Augmented and virtual realities

Let us first start by looking at the different environments that exist and the main differences between them. The obvious distinction between the terms real and virtual is shown to have a number of different aspects, depending on whether one is dealing with real or virtual objects, real or virtual images, and direct or non-direct viewing of these. An (approximately) three dimensional taxonomy is proposed by Milgram et al. [11] comprising the following dimensions: Extent of World Knowledge ("how much do we know about the world being displayed?"), Reproduction Fidelity ("how 'realistically' are we able to display it?"), and Extent of Presence Metaphor ("what is the extent of the illusion that the observer is present within that world?"). Moreover, Milgram et al. [11] suggested a reality-virtuality continuum (Figure 1) that can be used to distinguish between the different realities and their applications. On the left side, we have the real environment that solely consists of real objects. A simple example would be a video display of a real world scene or even viewing the same scene without any extra devices. On the right side, we find environments that solely consists of virtual objects. A simple example would be a simulator showing an imaginary farming landscape.

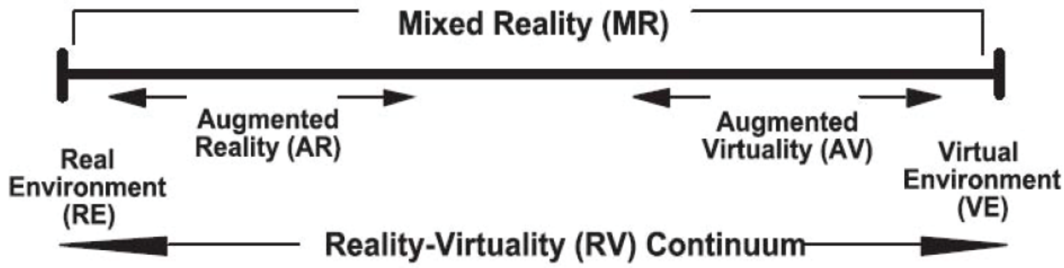


Figure 1. Reality-Virtuality continuum [12].

MR applications consists of both, real and virtual objects at the same time. This means any application between the two extrema of the reality-virtuality continuum is considered an MR application.

If an application is mainly consisting of a virtual world that is being augmented with real environment data then it is considered an "augmented virtuality" AV application. The other way around (augmenting the real world with virtual objects) is called AR. AR has become more dominant in MR applications in comparison to AV perhaps, due to more easily identifiable use-cases or technical feasibility.

AR according to Milgram et al. [11] is an augmentation of the real world environment through computer graphic enhancement of video images of real scenes, meaning AR refers to a live view of physical real world environment whose elements are merged with augmented computer-generated images creating an MR experience. The augmentation is typically done in real time and in semantic context with the environmental elements. Carmigniani et al. [13] agree with the earlier definition, however they put it in a simpler way by defining AR as a real-time direct or indirect view of a physical real-world environment that has been enhanced or augmented by adding virtual computer-generated information to it. AR adds information and meaning to a real place, object, or any other entity. It is characterized by the incorporation of virtual elements into the physical world as shown by the live feed of the camera, in real-time.

The common types of AR as suggested by Katiyar et al. [14] include the the following:

1. **Projection:** that uses sensors and virtual imagery to project some objects that the user can interact with like a virtual keyboard for instance.

2. **Recognition:** which uses the shape, faces, or any other real world object to provide relevant (supplementary) information (a simple example would be reading a barcode of a product to display some information).

3. **Location:** in which the GPS technology is used to allow the system to detect and locate the user to show relevant information related to that location like a guiding path to destination.

4. **Outline:** which is a type of AR where the human body, or part of it is projected making it a mean or a tool for the users to manipulate other projected objects.

AR solves one of the problems created by virtual worlds called the "vacancy problem" [15] in which a user is noticeably absent from one world whether it is real or virtual and present in the other one. In other words, since humans cannot be in both the real and virtual world at the same time, they should switch between these two according to their needs.

AR merges both of these worlds together to create a joint reality where the user benefits from both worlds at the same time. Using AR, gamers for instance can play games while still paying attention to what is happening in the real world surrounding them. While it has been reported that Pokemon GO players got into different accidents like car accidents for instance, The AR feature was not the element to blame. In fact the AR feature in the game was not very popular as we will see later in section 4.1.2.

Since AR games use digital devices to overlay game representations over the environment, one can say that they are pervasive [5] in the sense that they expand the environment by adding extra information to it which makes the player engaged in both world (real and virtual) at the same time.

2.4. Immersion and presence

Immersion and presence are concepts usually associated with virtual environments (VEs) and games [16]. These concepts have different meanings and definitions depending on how one perceives them. Psychologically, immersion is a concept that refers to the subjective impression that one is participating in a comprehensive and realistic experience [17]. When it comes to video game engagement, immersion can be defined as either the experience of becoming engaged in the game-playing experience while retaining some awareness of one's surroundings, or as the game's capacity to induce the feeling of actually being a part of, or present in the game environment [2].

However, Slater et al. [18] define immersion as an instrument to measure the technical performance of the displays in terms of their capabilities to deliver an illusion of reality to the senses of a human participant based on inclusiveness, extensiveness, surroundings, and vividness.

1. **Inclusiveness:** indicates the extent to which physical reality is shut out.

2. **Extensiveness:** indicates the range of sensory modalities accommodated.

3. **Surroundings:** indicates the extent to which this virtual reality is panoramic rather than limited to a narrow field.

4. **Vividness:** indicates the resolution, fidelity, and variety of energy simulated within a particular modality.

Presence refers to the sense of being there inside an environment [18] [19] [20]. Presence is often mixed with the immersion [20]. In fact some researchers such as Brown et al. [16] use the concepts of presence and immersion interchangeably when referring to the psychological state the gamers have when interacting with VEs. Brockmyer et al. [2] used the concept "spatial presence" to describe the experience of being integrated into a mediated environment such as VEs. Moreover, Brockmyer et al. [2] state clearly the difference between immersion and presence. As mentioned earlier, immersion is the ability of the game to draw the attention of the player into believing they are inside it. However, presence is the feeling of believing that they are inside the game world itself. These definitions by Brockmyer are used in this thesis to define both concepts.

3. AUGMENTED REALITY TECHNIQUES AND GUIDELINES

AR is not something new, in fact the first see-through HMD was invented in 1968 [21], it was called The Sword of Damocles because of its strange look [22]. However, in the last decade more companies started to invest in AR developing headsets and software development kits (SDKs). This competition along with AR's benefits made AR a huge thing. For instance Magic Leap, a Florida startup that seeks to develop new AR devices got over $4.5 billion funding [23] from different big companies such as Google, Qualcomm, Alibaba, and Warner Bros[1]. This huge amount of money reflects how much trust these companies have on the future of AR.

In this chapter, the three techniques used in AR applications to create the overall experience are described. These techniques are tracking, interaction, and display techniques. Each of these techniques will be discussed in detail to let the reader know about their current state, the limitations, and give some insights on what is expected to happen in each of them in the future. Moreover, three commercial see-through HMD displays will be described to show how companies are focusing on different aspects such as design, functionality, usability etc. Finally some guidelines for designing AR applications are described based on the literature.

The following techniques and categories are based on two popular surveys done by Zhou et al. [24] and Billinghurst et al. [25]. Zhou et al.[24] made an extensive review of ten years of The International Symposium on Mixed and Augmented Reality (ISMAR) papers and identified the main research trends over that time to be in the areas of tracking, user interaction and display technology. After that, Billinghurst et al.[25] extended the survey by adding newer techniques to the previously mentioned trends along with new trend called "social acceptance" which refers to how is the society going to accept some AR systems or devices such as HoloLens for example.

3.1. Tracking techniques

The tracking techniques refers to how the system can locate the user's device and its orientation in certain environment whether it is predefined or unknown. Tracking techniques are also called registration techniques since they allow the application to determine the position of the camera which help in registering the virtual objects position on the real environment.

The major techniques used for tracking are, sensor-based which purely uses sensors, vision-based which uses computer vision algorithms, and hybrid tracking which combines the two other methods.

3.1.1. Sensor based tracking

Using sensors like GPS/GLONASS, magnetometer, accelerometer, and gyroscope. The application can detect the position and orientation of the device with respect to its initial position. In a typical case, several sensors are used in collaboration in order

[1] https://www.crunchbase.com/organization/magic-leap/investors/investors_list

to provide a robust sensor-based tracking. The sensor based tracking is energy efficient since it does not use intensive algorithms. However, this efficiency comes with a downside that lower the accuracy of the tracking.

3.1.2. Vision based tracking

Another alternative to locate the device is using image processing to detect a physical or a virtual marker and keep tracking of it. This can be achieved using one of the following methods:

1. **Marker Based (Fiducial trackers):** Using predefined images, the application can use the device camera to get a video stream and then use image processing to detect those images, extract their identifier (ID) and locate the user's camera relative to that image. An example for such applications or games would be Invizimals [26] which is discussed in Section 4.1.2. Markers helps in reducing the computational power from the image processing algorithms, as we will see later, markerless AR requires intense computational power that might not run on old hand-held devices. Markers have high accuracy since the information needed to produce the augmentation is physically there (the marker or target image) so the only way to lose the virtual information is by losing track of the image target, but it is easy to recover the tracking since the user will only need to look at the target image again to regain the augmentation. However, the fiducial markers suffer heavily from the bad lighting of the environment since it does affect the image quality and it will become impossible for the application to detect the markers if the environment is nearly dark. Moreover, markers need to be set before running the application, and that is why marker-based applications are not that scalable and are mainly used indoors since it will require huge efforts to set up and position the markers in a larger area such as a city for instance. In addition to that, the size of the marker and the quality of the camera determines the maximum distance the user can use be in away from the marker while the application can still detect the marker.

2. **Natural Feature Extraction and Model based Tracking (Markerless AR):** Markerless AR is a term used to denote an AR application that does not need any pre-knowledge of a user's environment to overlay 3D content into a scene and hold it to a fixed point in space. Usually it refers to the tracking techniques that use computer vision to extract natural feature of the user's environment to recognize objects, or construct a model of the scanned environment itself. Since this approach does not require any predefined images, it is suitable for large spaces or outdoor applications such as navigation applications. However, these algorithms require more computational power, and hence consume more energy than the marker-based approaches. But since the computational power of the AR devices (smartphones and HMD) have improved, using such intense algorithms is not a problem anymore with the newest devices. The most common and popular algorithm concept is called SLAM (Simultaneous Localization and Map Building) which was originally invented for robot navigation in unknown environments [27] and later it was adapted to be used in AR [28]. The algorithm

allows tracking inside unknown environment by incrementally building a map of it while driving or walking in it.

Sensor tracking can also be said to be "markerless" in a sense that it does not require any predefined images or references for the environment. However, the accuracy of sensor based tracking is incomparable to the vision based algorithms and this is why vision based tracking has become increasingly popular in recent times due to the minimal hardware requirements, improved computational power of consumer devices, and the ubiquity of mobile devices. [25]

3.1.3. Hybrid based tracking

Hybrid based tracking is a combination of sensor tracking and vision tracking in which sensor data is used to increase the accuracy. A simple example of this technique would be using the gyroscope and accelerometer data to recover from marker loss.

3.2. Interaction Techniques

Interaction techniques refer to techniques that allow the users to interact with the virtual content available in the application.

3.2.1. Traditional interfaces

The traditional 2D user interfaces (UI)s such as mouse, keyboard, or touch screen input can be used in AR applications as well [25]. These interfaces are easy to use since most of the users are familiar with at least one of them.

3.2.2. Tangible interfaces

Tangibles are physical objects that act as a bridge between the real world and the virtual one. These objects can be manipulated by the user in real world to interact with content in the virtual one. Tangibles are powerful tools because they use physical objects that have familiar properties, physical constraints, and affordances, making them easy to use. It should be clarified that affordance in this case refers to the actionable properties, which suggests how the object should be used. [24]

3.2.3. Natural interfaces: body motion and gesture

Natural interaction methods that humans use with each other such as body motion, hand gestures, speech etc. can also be used to provide a more intuitive interaction. [25] Body motion can be tracked and recognized using various types of motion tracking sensors that user can wear. Various motion sensors of different size and shape can also be applied in AR applications, ranging from a glove type device used for tracking hand gestures to full body motion tracking systems such as Vicon[1] and Xsens[2] motion tracking suits for instance. Cameras and image processing is an alternative for tracking the user motion without the use of expensive hardware but this will require more computational power depending on the tracked motion. Speech input is also a good interface that can be used to make hand-free applications. However, the speech interfaces usually suffer from the environment noise and can be uncomfortable to use for some user in public. [29]

3.2.4. Hybrid interfaces

The last type of interfaces is the hybrid user interface that combines a variety of different, but complementary interfaces. Thus, a flexible infrastructure for hybrid user interfaces should automatically accommodate a changing set of input and output devices and the interaction techniques that use them. As a result, the operations that the system supports will be more than conventional ones and can even be extended to allow users to specify new operations at run time. However, combing different types of interfaces might make the system sophisticated for the users.

3.3. Display Techniques

The display techniques refer to the hardware that allows the user to see the augmented environment. Currently, there are three different display techniques for AR applications, see-through HMD, hand-held displays, and projection based displays.

3.3.1. Head mounted displays

HMDs are displays placed on headsets that can be worn by the users. HMD can either block the user's entire vision from the real world by replacing it with virtual content which is mainly used for VR. However, see-through HMDs allow the user to see the real world with virtual objects superimposed on it by optical or video display which is the reason we have two types of see-through HMDs: (1) optical see-through (OST-HMD) and (2) video see-through (VST-HMD). OST-HMD displays allow the user to see the real world with their natural eyes and which overlay graphics onto the users' view by using a holographic optical element, half-silvered mirror or a similar technology. [24] VST-HMD allow the user to view a video stream of the real world in real time augmented with virtual content. The advantages of VST-HMDs include consistency between real and synthetic views, and availability of a variety of image processing techniques like correction of intensity and tint, blending ratio control. [24] However VST-HMDs suffers heavily from the camera delay which makes them hard to use in real life scenarios and that is why the OST-HMDs are getting more popular since they solve that issue and that is because they do not need to render the real environment

[1] https://www.vicon.com/
[2] https://www.xsens.com/products/xsens-mvn/

since it is already there. Head mounted projection displays (HMPD) are an alternative to HMDs. They typically use a pair of miniature projectors mounted on the head that project images onto retro-reflective material in the environment which is then reflected into the users eyes. This type of displays are discussed in more details in 3.3.3.

3.3.2. Hand-held displays

Displays of mobile devices form what is called hand-held displays, these displays are very cheap and more affordable compared to the see-through HMDs. In addition to that, most of those devices have higher resolution than the HMDs in general. Moreover, they are minimally intrusive, socially acceptable, readily available and highly mobile. [24]

3.3.3. Projection based displays

HMD and hand-held displays are targeted for one or few users only. If the application is meant to be used for a large number of users located in the same place, projection based are the best solution. projection-based display uses projectors to project the information needed on real objects or surfaces. A simple example could be a wall projection in a museum, where users are not required to wear or use any specific hardware to see the projected virtual content but they might need an extra hardware provided by the museum to interact with it. Projection-based displays are good option for applications that do not require several users to wear anything, providing minimal intrusiveness. [24]

3.4. Smart Glasses

Displays play a big role in AR since they play the role of a “window” that allows the user to see the virtual objects as mentioned earlier. One particular type of display is seeing a breakthrough which is expected since big companies are investing in it. It is an OST-HMD also known as smart glasses. In this section, three different smart glasses that were developed by different companies in different periods of times are described. The comparison between these three devices demonstrates how this technology evolved drastically during the past four years.

3.4.1. Google Glass

In 2013, Google launched the first smart glasses available for public under the name of Google Glass. The Google Glass (Figure 2) look like simple glasses with a sci-fi feature in the upper right part of the right lens which is a small display. The glasses offer hands free interaction features, such as using voice commands. However it also has a small button on the top right that the user can use to interact with the glasses.

Figure 2. Google glasses [30].

The glasses runs on Android 4.0.4 (Ice Cream Sandwich) with a 570 mAh Lithium battery, OMAP 4430 SoC dual core processor, 16 GB of memory storage capacity in which 4 GB of it is for the OS [31], 1 GB of RAM, and a bone conduction transducer for the sound which allows the glasses to transmit the sound through the skull meaning there is no need for extra earphones or headphones [32]. Google Glass came with over 50 applications including Google Maps, Gmail [31]. The major critics the glasses got was about privacy and security issues, for example the glasses can take pictures without the permission of the user [32], and record conversations, which led to its ban in many establishments [33]. Moreover, the glasses were not really appreciated in the society at all. For instance the media invented an offensive word (glasshole[2]) that describes those who use the glasses intensively. The €1,500 price also played a major role on making the glasses a "failure" or a disappointment [31] since not many people would be willing to pay that amount of money for a device that can barely do what a smartphone. This resulted in ceasing of the glasses' production in 2015.

3.4.2. HoloLens

In March 2016, Microsoft released its first AR/Holographic glasses also known as HoloLens. Unlike Google Glass, HoloLens (Figure 3) does not resemble anything like ordinarily glasses; they are much bigger than the average glasses and look more like a headset than normal glasses and that is because Microsoft focused more on the functionality rather than the design or the look of the glasses [34]. HoloLens runs on Windows Holographic [35], which is a modified version of Windows 10. The glasses can access the Windows store and run any Universal application available there [36].

Figure 3. The Microsoft's HoloLens[1].

[2]http://www.urbandictionary.com/define.php?term=Glasshole

The glasses have some interesting hardware, starting from the sensors; it has one depth camera with a field of view (FoV) of 120 °×120 °[37] which is near to the vertical FoV of the human eye (200 ° x135 ° [38] [39]). In addition to that, the glasses are equipped with other four environmental understanding cameras (two on each side) that can map the area surrounding the user, and an ambient light sensor. These sensors allow HoloLens to map spaces and get accurate information about the environment along with the user's position inside it[40]. HoloLens has four microphones to improve the voice command accuracy. Moreover, it has an inertial measurement unit (IMU) which consists of an accelerometer, gyroscope, and magnetometer, coupled with the cameras; it enables HoloLens to know where the user's head is and how it is moving [41]. Finally, the glasses have a 2MP camera that allows taking both photos and videos. For the computational power, the glasses have an Intel Atom x5-Z8100 64-bit CPU [42], you can notice that the CPU is 64-bits however the OS is only 32 bits. For the GPU, the glasses use HoloLens Graphic made by Intel as well. What really makes HoloLens standing out from the other glasses is its Holographic Processing Unit (HPU), which integrates data from HoloLens's sensors (accelerometers to detect motion and a Kinect-like camera system to detect depth). The HPU uses the sensor data to recognize gestures, maintain a map of the environment, and ensure that virtual 3D objects retain their position in the real world [43] [41]. Microsoft did not reveal the FOV of the HoloLens, however few people tried to approximate it and estimated it to be around 33.4 [44] and 30 [45]. For the development environment, Visual Studio and Unity 3D are the only tools required to build a holographic applications for HoloLens.

3.4.3. ODG R7

Finally, we have the ODG R7 glasses that were used in the evaluation of Ghost Hunters game developed for this thesis. In the Consumer Electronics Show 2016 (CES), the Osterhout Design Group (ODG) revealed their R7 smart glasses. Similar to the Google Glass, the R7 (Figure 4) looks like ordinary glasses with thicker edges. The only thing that distinguishes the R7 from a normal pair of glasses is its front camera. The R7 runs on ReticleOS, which is a see-through optimized Android framework for head-worn computing atop Android Kit Kat (4.4.4). The glasses have multiple IMU which include 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer.

Figure 4. The ODG R7 [46].

[2]https://www.microsoft.com/en-us/hololens

The Qualcomm SnapdragonTM 805 2.7GHz quad-core Processor is used in the glasses making them the most advanced glasses in 2016 in terms of computational power [46]. For the display, the glasses contain dual 720p stereoscopic see-through displays that handles up to 80fps with 80% see-through transmission along with magnetic removable photochromic shields that can make the glasses usable in bright environments. R7 offers a variety of environment sensors (ambient, humidity, and altitude) along with the GPS. These sensors can make the glasses useful not just to entertain people but also to provide some services such as locating the user or detecting the humidity of the environment for instance. Moreover, having an Android atop OS make it easier for the developer or even companies to target both hand-held devices users (smartphone and tablets) and R7 as well and that was the main reason why these glasses were chosen to be used in this thesis.

3.5. Challenges in augmented reality technologies

AR faces technical challenges in all three major techniques mentioned earlier. The tracking techniques suffers heavily from the computational power since they consume a lot of energy hence draining the battery of whatever device they are running on. That is why optimizing these algorithms for mobile device are needed [25]. For the displays, the see-through HMDs are promising especially that big companies are spending enormous amount of money on them. However, they are still not affordable, have narrow FoV with low resolution and a noticeable latency sometimes for VST-HMDs, cause fatigue and eye strain [47], and not socially accepted yet. Moreover, the OSTHMD suffers heavily from the surrounding luminance. Finally, since the glasses are not commonly used, the interaction within them lacks research and this thesis tries to explore an aspect of it.

So before AR becomes accepted as part of user's everyday life, just like a mobile phone and a personal digital assistant (PDA), issues regarding intuitive interfaces, costs, weight, power usage, ergonomics, and appearance must also be addressed.

3.6. Guidelines for application design and development

Despite the fact that AR still has limitations, a pleasant user experience can be provided if the AR application is designed properly. In this section, AR guidelines found in the literature will be discussed. All of these guidelines except for the "using social media" were taken into account when designing Ghost Hunters.

Wetzel et al. [48] made a list of guidelines for AR games. The list consists of 12 elements from which, few are specifically related to games and game experience. However, most of them can be extended to general applications. The list of Wetzel et al. [48] is as follow:

1. **Experiences first, technology second:** Most games focus on the technology more than what can the technology offer to the game itself. Therefore, instead of making certain technology as a tool to serve the overall experience, designers were focusing on doing everything they can with the technology and use the most

of it.This is something wrong because you do not need to saturate the experience with plenty of features because it will make the system complicated.

2. **Stick to the theme:** As mentioned earlier, technology should be a tool to make the application and not the application itself. Selecting relevant technologies that help us achieve our user experience is the designer's first priority.

3. **Do not stay digital:** Since AR applications enhance the real world, they do not necessarily have to focus entirely on digital content. One can be creative and use different objects, cups, signs, posters, tables, etc. to create an enjoyable experience.

4. **Use the real environment:** AR applications can be used indoors and outdoors, try to use this property (space) in shaping and extending the user experience.

5. **Keep it simple:** Some applications focus on complex interaction and using many technologies, which will make the user frustrated and confused. As a designer, you need to focus on simple and clear interaction schemes and avoid situations where trying new technologies becomes the key consideration.

6. **Create shareable experiences:** Within AR games, other players and even non-players may become interested in the content of the game. Same goes for general applications, when people are using smartphones or tables outside and bypassers notice them, they can easily ask the users to let them see what they are doing with that application. A HMD cannot allow such a feature unless it is connected to another display and share the same content.

7. **Use various social elements:** Interacting with real people as part of the game always adds another layer of excitement compared to having only virtual characters.

8. **Show reality:** Do not overwhelm the screen with augmented content, leave some space for the "real" object and world to appear, what is the point of augmenting the real world if the real world is not there in the screen?

9. **Turn weaknesses into strengths:** Every technology has its limitations, poor GPS or WiFi signals, high computational power, etc. The application should adapt to these limitations and maybe use them as advantages. For example if the application uses a lot of resources and drains the battery fast, make a timer that force the users to close it or automatically shut itself down when it is not needed.

10. **Do not just convert:** Some applications and games try to clone an existing product like Pacman, or Super Mario, for example, and try to adapt it to AR and MR worlds without taking into account the differences between AR/MR and general applications. Maybe copying an application will appear exciting in the beginning, but that excitement might not last and the application will not be that engaging after some time.

11. **Create meaningful content:** AR adds very interesting visual features to applications by bringing virtual 2D/3D content into the real world. This content should be meaningful and really make use of its possibilities.

12. **Choose your tracking wisely:** Realizing and applying new and potentially better tracking methods is always of importance for the development of AR applications and games. One should be well aware of the flaws in the chosen method and consider if they distract too much from the actual user experience.

4. PERVASIVE GAMES

In this chapter, the evolution of pervasive games is examined and how they evolved from research prototypes to commercial products. After that, some pervasive games from each generation are described for a better understanding of these generations.

4.1. Pervasive game generations

As mentioned before, pervasive games are games that extend the playground beyond just a screen. This can be done by using the location of the user, the environment data surrounding the user, or even the people whom the user is spending time with. Kasapakis et al. [49] defined six criteria to evaluate pervasive games. The criteria include: (1) the equipment used in the game; (2) the content of the game; (3) the orchestration, which refers to whether the game requires a "supervisor" (game manger) to instruct and help the users during the game sessions; (4) the localization and the context awareness of the game which refers to how much the game knows about the user and the environment; (5) the methods and technologies used for communication; and finally, (6) the evaluation methods of the academia games. Based on those criteria and the time period, Kasapakis et al. [49] proposed a categorization of pervasive games. Table 1 shows the different categories and their characteristics.

Table 1. The generations of pervasive games.

Generation	First generation	Second Generation	Third generation
Time Frame	2002-2009	2009-2014	2014-onwards
Localization	GPS, self reporting, no localization	GPS/Cel-ID	GPS, proximity-based localization/ crowdsourcing localization platforms
Communication	WiFi, Bluetooth, Zigbee	WiFi,3G, Zigbee	WiFi WiFi Direct 4G
Context	Captured by external sensors	Captured by build-in sensors	Captured by built-in sensors/3rd party web services
Orchestration	Heavy/light orchestration actions	Light/No orchestration actions	No orchestration actions
Player Equipment	Custom equipment, wearable computers, PDAs, feature phones	Smartphones	Wearables (glasses, smart watches, health bands...etc)

According to [49], pervasive games went through three different generations in which, every generation has its own period of time, means of communications, and equipment. In the following sections, each of these categories is described in detail.

4.1.1. First generation

The first generation of pervasive games took place between 2002 and 2009. Games of this generation mostly used GPS to locate players. Although some games used self-reported positioning or did not have the localization feature at all. WiFi, GPRS, and Bluetooth have been the common communication solutions. User and environmental context incorporated into the game rules has been mostly obtained via external sensors. Most games required orchestration, meaning experts or actors that were needed to run the game as moderators. Finally, the equipment used to play these games were mostly PDAs or custom wearables and that is why most of these games were only research projects. Some early prototypes of pervasive games that belongs to the first generation of pervasive games are discussed below.

1. **Can You see Me Now (CYSMN)** [50] Can You See Me Now? (CYSMN) is a game of "catch the player" but with a twist. Online players (PC users) are chased through a virtual model of a city by 'runners' or street players (PDA players), who have to traverse the actual city streets in order to capture the online players. The game uses GPS and WiFi to locate and provide wireless network connection to the runners. The online players were spawned in a random predefined location on the virtual map.

2. **TimeWarp** [51] is mobile outdoor AR game for exploring the history of a city in the spatial and the temporal dimension. The game is staged in the old part of Cologne, within an area of about 1.5 square miles. As the players walk around they have to find places relevant to the game so that they can interact with the various game elements. Three different types of game locations are implemented:

   (a) Time portals (leading to other time periods (Figure 5)

   (b) Markets to buy items that are required to solve challenges

   (c) The challenges themselves.

Figure 5. The same marketplace in different time periods (medieval – left, roman – right). [51]

3. **The Sensorium** [52] family of games provides a platform and environment for multi-player games in a pervasive environment. Each player is equipped with

a mote, which (along with those of other players) is an element in a wireless sensor network. Sensorium games are pervasive in the truest sense. That is, sensory events in the environment trigger events in the game. For example, walking under a light may cause a loss of game lives.

4. In **Epidemic Menace** [53], players takes the role of medical experts who seek saving the mankind threatened by a mutated virus. A villain scientist, creates a lethal mutation and contaminates a university campus with it. From there the virus spreads and infects all humans. Teams of experts – the players – are assigned the task of defeating this threat. They have three hours in which to destroy the virus before it escapes the campus. The teams must also uncover where the mutant virus came from and how it came to be. Epidemic Menace is a collaborative game. Each team has a room equipped with stationary devices that allow players to observe and analyze the virus and to communicate with other team members. In addition to the stationary devices in the game room, each team receives a set of devices that can be used outdoors to capture and destroy the virus. Players are tasked to clear the campus of the threatening virus and to stop it from spreading by uncovering the conspiracy behind it. The gameplay is introduced by a movie featuring evidence provided by a police witness and printed testimony based on the evidence. Depending on their individual scores, players are given a number of observation tapes during the game. They are also are asked to uncover the conspiracy and to stop the virus from spreading.

4.1.2. Second generation

The second generation started to emerge around 2009. The games belonging to this category use GPS for localization and WiFi/3G for communication. They were mainly running on smartphones and since smartphones are equipped with built-in sensors, it was easy to exploit them for capturing user and environmental context. Finally, second generation games are less dependent on orchestration (their scenarios rarely require the presence of actors or experts) and since smartphones are widely used and socially accepted, a lot of companies invested in these games and made huge profit such as Sony Computer Entertainment's Invizimals that started as an AR game and then expended into toys, trading card games, comics, and an animated TV series.

1. **Ingress** is an AR game that uses player's GPS to position the user in the virtual world. The AR feature allow users to see an alternate world that relates back to the current world. In other words, by using a device as a kind of lens, users can see the current world, but augmented with additional features (Figure 6), objects, or information [54].

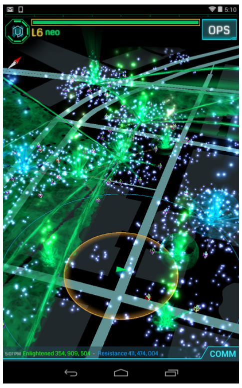


Figure 6. In game footage of Ingress[1].

The main concept of the game is to join one of the two available factions and help it to capture “portals” which are located in real life places. This means that players must visit the portals in real life to capture or defend them. The game has more than 10 million downloads (August 2017).

2. **Zombies, Run!** A smartphone application that mixes exercise with video gaming. The game takes the player into a post-zombie-apocalypse world in which they play the role of ’Runner5’, responsible for going on runs out into zombie territory to retrieve supplies and rescue stranded survivors. To play the game, the user must plug headphones into his/her smartphone, select a mission in the application and go for a run outside. Using GPS, the gamer tracks the player’s speed and distance, the story unfolds via audio-clips played through the headphones as the player runs. The missions can take 30 minutes or 1 hour and in between

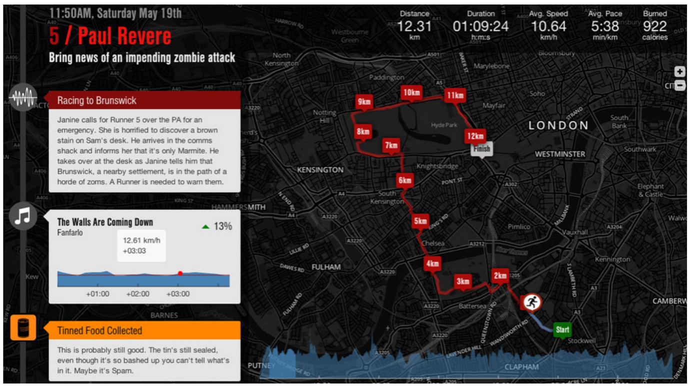


Figure 7. Screenshot from Zombies,Run![55]

the player will hear songs of his/her own selection. What makes this game most unique is that at any time during a run the player can be attacked by zombies and will have to increase his/her speed by 20% during the attack to survive. Zombie attacks are simulated with a warning message and then the groaning sounds of Zombies getting closer and closer until the player either evades them or is consumed. Fortunately, for players, being caught by zombies is not the end of the world, but will result in a loss of potentially valuable supplies. [56]

[1]https://play.google.com/store/apps/details?id=com.nianticproject.ingress

3. **Luostarinmäki Adventure** [57] is an AR adventure game in Luostarinmäki open-air museum, Turku, Finland, as a part of the Futuristic History research project. Provided with an iPad, the player of the Luostarinmäki Adventure can explore the area and be able to see not only the buildings that are actually there, but also the people and the life in the 1850's as digital layers added on top of the camera view.

Figure 8. A player interacting with the environment in Luostarinmäki Adventure [57].

The game mechanics are based on interaction between the player, the virtual characters, and the real-world environment (Figure 8).

4. **Invizimals (2009)** is a collectible-creature-game for Play Station portable (PSP). Similar to Pokémon, Invizimals involves players capturing and raising different species of creatures called inviZimals (Invisible Animals) and battling other users or an artificial intelligence (AI) opponent with them.

Figure 9. Two inviZimals fighting[1].

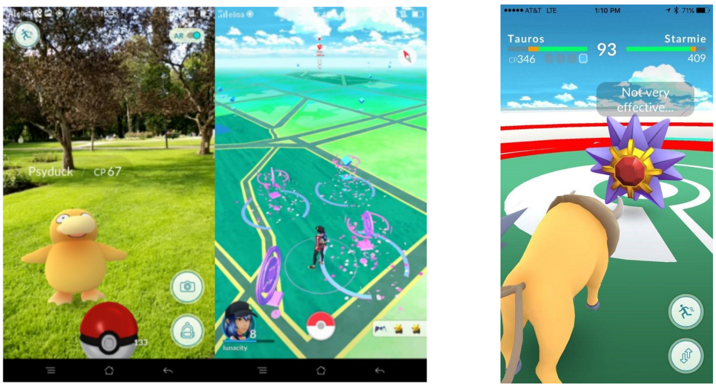
Unlike Pokémon, Invizimals requires the player to hunt and capture these creatures within the real world, using AR (a camera attachment to the PSP is used to get the video feed) and a physical "trap", i.e. an AR marker (Figure 9). Monsters are spawned at different environments determined by the color of the surface and the time of day. These monsters are then trained and pitted against opponents

[1]https://www.playstation.com/en-us/games/invizimals-psp/

in the physical environment, as they can be seen through the camera lens of the PSP around the AR marker. Besides the marker, the game also detects colors and brightness values of physical surfaces. The AR marker can be used to view the monster collection and take pictures of it [26].

5. **Campus Knights** [58], a location based MR game that is played by teams, using mobile phones inside several indoor arenas that have both physical and virtual representations. Each game round begins with players exploring the physical world to recover digital artifacts, and culminates in a boss fight inside a 3D virtual replica of the physical game arena.

6. **Pokémon Go**, a location based that follows the Pokémon game series. In the game, the player creates an avatar that represents them and then use “Poke balls” to hunt the Pokémons around the city that where they are located (Figure 10a). After reaching level 5, players can choose one of the three available factions (Teams), the Instinct (Yellow), the Mystic (Blue), and the Valor (Red). Teams are like guilds that fight over territories called "gyms". The player can help



(a) Two in-game scenes from Pokémon GO)[59].

(b) A gym battle in Pokemon GO.

Figure 10. In-game footage from Pokemon GO.

his/her guild by using his/her Pokemon to either defend gyms owned by his/her guild, or attack the other guilds. Users can also evolve their Pokemons making them strong enough to capture or defend "Gyms"(Figure 10b). The game is quite popular and has over 100 million downloads (August 2017). This popularity is also visible in the academia, a Google Scholar[1] search with keywords "Pokemon go" leads to over 15000 results, if we filter the results to show only the papers published after Pokemon GO was published (2016), we get around 5000 results. The game has an AR feature that allows the player to see the chased Pokemon on the top of the real world. Surprisingly, AR features, safety issues or the free-to-play revenue model did not receive considerable feedback from the users [59].

The game got a lot of criticism since it increased risk of injury, abduction, trespassing, violence, and cost. [60]

[1]https://scholar.google.fi

4.1.3. Third generation

After introducing Google's Cardboard and Google Glass, the focus of pervasive mobile games switched back to wearables again, but this time the hardware is much powerful, reliable, but unfortunately, not yet affordable for end users. The research on third generation is still lagging and that is due to the difficulties and the high cost of the equipment involved in it. This thesis will help understanding more about the third generation of pervasive games and give more insights about the interaction techniques and usability of the devices used today. So far, most of the research involving smart glasses does not focus on entertainment and instead, it focuses on services such as health care, architecture, and industry. However, we can find few 3D generation commercial games, made by Microsoft to showcase the potential usage of its HoloLens.

1. **Fragments**: A sci-fi crime-drama MR game developed by Microsoft in collaboration with Asobo Studio. The game turns the entire playing room into a crime scene filled with hidden clues which sometimes lay under the real furniture of the room that the user can see through HoloLens. The player must find these

Figure 11. A clue as seen by the player [61].

   clues (Figure 11) to solve the crime case. The game also features life-sized holographic characters who are aware of the player being present and interact with him/her along with the surrounding space as if they were really in the room[1].

2. **The Floor is Lava** is an AR HoloLens game that turns the surrounding floor into a lava by scanning the environment prior to starting the game in order to map out the interactive area. If all goes well, The Floor is Lava overlay the floor with virtual lava that the user should avoid touching while moving in the room (Figure 12). There is even a scoring system to it, which requires the user to head toward floating ice cream cones and yell out "Nom!" to gulp them down. The lava's graphics frequently overlap with thinner elements scattered across the floor or disappear entirely. [62]

[1]http://www.asobostudio.com/games/fragments

Figure 12. footage from Floor is lava [62].

3. **RoboRaid** is an AR first-person shooter game that uses natural movements to target enemies coming at the player from every possible direction. The game spawns holes in the walls of the room making robots able to enter the playing area. The player can "air-tap" using his/her fingers to shoot the evil robots. The game also has spatial audio to orientate the player in order for him/her to dodge the enemies' bullets by moving away from them in the physical space.

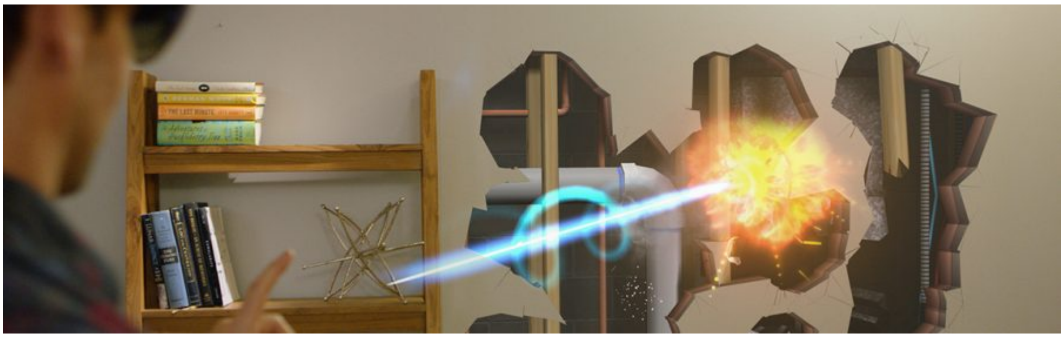


Figure 13. Footage from the RoboRaid trailer [63].

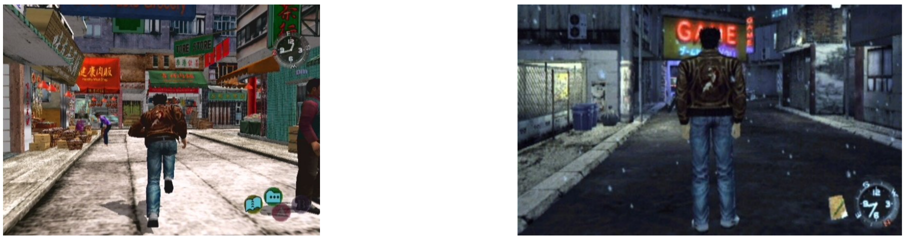
The cracks in the walls (Figure 13) give a good augmented depth in stereo when you watch the playing area being destroyed. The enemies are small enough to fit into the screen at a typical room distance and the cracks in the wall also do not fill up the whole wall from top to bottom. Only one crack per wall appears so that the user does not notice the limited FOV too often. [63]

4.2. Environmental data in pervasive games

In this section, three games that use data from the environment are presented. Two of those games are commercial games which were popular in their times. The third game is a research prototype with a unique and interesting idea.

1. **Shenmue**, an open world adventure game where the player controls martial artist Ryo Hazuki (Figure 14) who wants to avenge the murder of his father in 1980s Yokosuka, Japan. Shenmue consists of persistent open-world 3D environments

where shops open and close, buses run to timetables, and characters have their own routines, each in accordance with the in-game clock. Algorithmically generated weather and day-and-night cycles were implemented with reference to meteorological records of 1986 Yokosuka [64].



(a) Street in the morning [65].

(b) Street at night [66].

Figure 14. Screenshots from Shenmue.

2. **Boktai**, an action game for GameBoy Advance where the player take the role of a Vampire Hunter called Django who wields a weapon called "Gun Del Sol" (Solar Gun). Boktai's game cartridge includes a photometric light sensor that measures the light exposure.

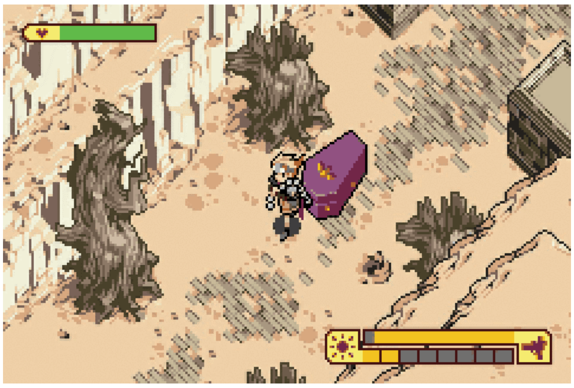


Figure 15. Django dragging a Boss coffin [67].

In order to charge the in-game weapon, the player must take their Game Boy Advance outside daytime. The players' gun can also run out of charge with dire consequences. In addition, once a boss is beaten, you must drag its coffin (Figure 15) to the entrance of the dungeon where a special device, the Solar Pile, awaits to convert real-life sunlight into special beams that burn the monster away once and for all. [67]

3. **Mythical: The Mobile Awakening**[68] is a mobile pervasive multiplayer game. In the game, players are wizards and have access to a magical parallel world. The game world is divided into four factions (Dawn, Sun, Dusk, and Moon) each with their own mysteries and skills.

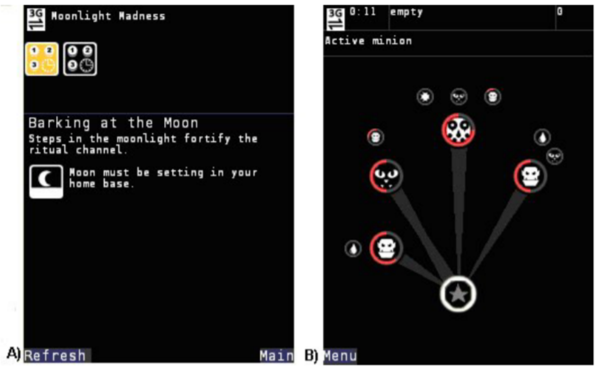


Figure 16. Screenshots from Mythical: the Mobile Awakening. A) Ritual gameplay. B) Encounter gameplay [68].

> The players can develop their skills by performing several rituals (Figure 16 A). To cast a ritual, they have to find the perfect place and time consisting of temperature, cloudiness, time, astronomy, location and social context (some rituals require more than one person to cast (Figure 16 B)).

4.3. Lesson learned from pervasive games

The first generation of pervasive games demonstrated that pervasive games can be very immersive even if the hardware required to play the game is burdensome or heavy to carry. Although Ghost Hunters does not use custom hardware that is hard to carry, it does use expensive glasses which are not yet affordable by the majority of the players.

Sensorium and Boktai showed us that using surrounding light data can make games more engaging and more fun to play. However since no work have been done on using such data in AR games, the work of this thesis aims at exploring the potential use of light data in AR games.

Invizimals showed us that hand-held AR games are engaging even if they use a marker, they can still attract a large number of gamers and non-gamers. In addition to that, outdoor pervasive games such as Pokemon GO, has shown us how dangerous such games can be if the designed poorly in favor of one of the two worlds (real and virtual) as the game lures the players to certain locations while distracting them from their surroundings completely.

The current 3rd generation games proved that markelress AR are truly immersive thanks to the advanced hardware and sensors that can track both the user and the environment. However all of those games runs on HoloLens which is not affordable by the average consumer. In addition to that, most of the available mobile devices do not have such tracking sensors. For this, the prototype implemented in this thesis was developed as an Android game that can run on both smart glasses and smartphones, making the game more available to the players.

5. DESIGN AND IMPLEMENTATION

After defining the essential concepts and introducing the current state of the art of pervasive games, it is time to talk about the artifact developed in this thesis. The Ghost Hunters game that was developed to measure the usability of hand gestures and buttons in smart glasses and smartphones is discussed in details. The chapter begins with a description of the design process used in this thesis and justify the final design. Afterwards, the concept and its important features are described. Next, the UI of both the smart glasses and smartphones version of the game will be described. Finally, a technical part that describes the overall system and its component will conclude the chapter.

5.1. Design process

The design process was a combination of waterfall and iterative design (Figure 17) that has three major phases:

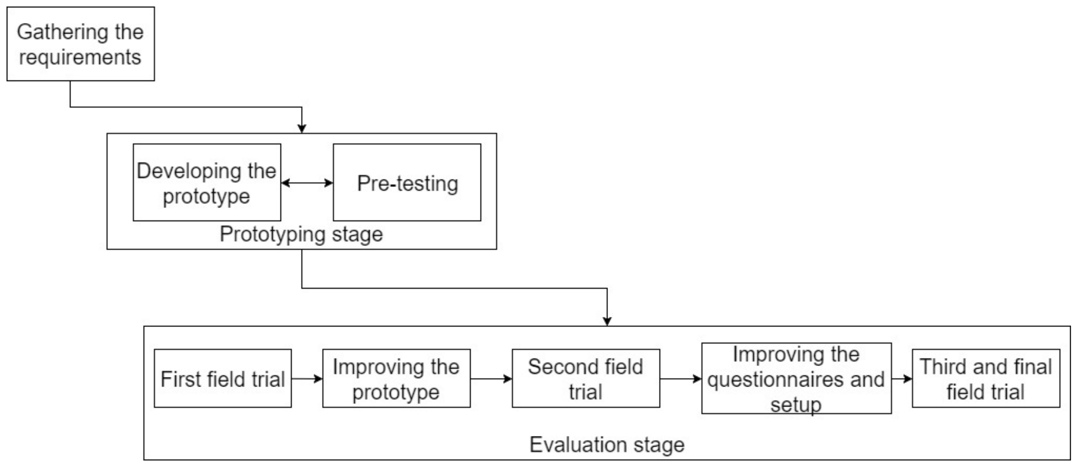


Figure 17. The design process diagram.

1. **Gathering the requirements:** the work started initially from the literature survey where information about pervasive games, AR, and the available hardware and software were gathered and analyzed.

2. **Prototyping stage:** afterwards, the game prototype was built and its usability was tested by a very small group of users in an iterative phase. Based on the feedback, the prototype was improved till the test users were satisfied with the results.

3. **Evaluation and improvement stage:** after getting a satisfactory prototype, a larger group of users tested the prototype in the first field trials. Again, based on the results, the prototype was improved. After that, a second field trials was conducted which revealed some inconsistencies in the questionnaire and the evaluation setup. These pieces of information were taken into consideration when designing the final evaluation process and setup.

5.2. Design justification

Initially, three alternative designs were suggested based on the location detection mechanism, tracking mechanism, and hardware used. These three designs were (1) marker-based AR game; (2) hybrid AR/VR game; and (3) markerless AR game.

1. **Marker-based AR**. In the first design, a mobile game in which ghosts are located in some physical items around the campus was suggested. The player must find these items and exorcise the ghosts that "live" in them before the time limit.

   Why the idea was dropped?

   (a) Asking the user to scan items will make the game more predictable meaning it loses the element of surprise.

   (b) Using marker-based AR requires orchestration (setting up the QR codes or markers in the campus) which will decrease the scalability of the game.

   (c) Using hand gestures can interfere with the marker-based tracking system since the user's hand might hide the marker while interacting with the system.

2. **Hybrid AR + VR**. The second idea involved both AR and VR technologies. The players would be asked to find hidden "portals" (QR codes/markers) that can take them to the ghost's world (a virtual world) where they can fight them.

   Why the idea was dropped?

   (a) The same with the "Marker-based AR", using marker-based AR will make the game poorly scalable.

   (b) Using VR in smart glasses (ODG R7) with hand gestures as input is not practical since the glasses are OST, which makes the VR experience not engaging.

3. **Markerless AR**. The third design involved making a markerless AR game which means an AR solution that does not use any markers or target images, an example of this would be Pokemon GO. Since the game is a role playing game where the player takes the role of a ghost hunter who uses "futuristic goggles" to see and capture the ghosts that live in the campus, the markerless AR is perfect for the story.

5.3. Game concept

Ghost Hunters, is an AR "catch the monsters" game where the player takes the role of a ghost hunter equipped with high-tech goggles that allows him/her to see ghosts and capture them. The goggles are used to see ghosts and capture them using a "virtual laser" generated by the glasses. The goggles (in-game) use the light of the environment to charge, this means that the players must constantly find bright areas to keep their goggles on. To beat the game, the player must capture all the ghosts that move in the campus area, which can only be reached by moving (walking) to them in real life. The game has two losing conditions, the player runs out of time (3 minutes) or the Goggles' battery reaches 0%.

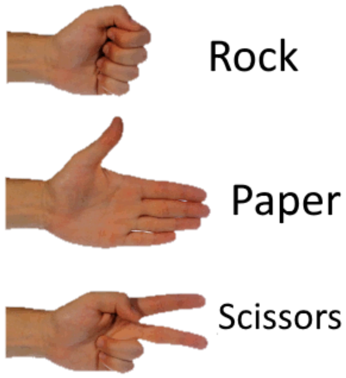


Figure 18. The hand gestures used in Ghost Hunters.

The gesture that the player has to perform in order to capture a particular ghost depends on the ghost type that he/she is seeing. To make the interactions more natural, the "paper, rock, and scissors" gestures were used to interact with the ghosts which have the same three types including rock, paper, and scissors. In order to capture these ghosts, the player has to do the gestures that can beat that type of ghosts as if he/she is playing a real paper, rock, scissors game against it (Figure 18). This means that a rock ghost can be captured with a paper hand gesture, paper ghost can be captured with a scissors hand gesture, and the scissors ghost can be captured with rock hand gesture. The reason behind using the paper, rock, scissors as metaphor is that this traditional game is popular with a well known hand gestures that are easy to explain and describe to test users.

5.4. Interaction methods

For the interaction methods, hand gestures and buttons were used. The hand gesture interface is the same for both devices (smart phone and smart glasses). However, for the button interface, the smart phone version have virtual buttons while the smart glasses have physical buttons and that is because the smart glasses' displays are not touch sensitive.

5.4.1. Hand gestures

The first interaction method is the natural hand gestures. As explained before, the game uses the traditional paper, rock, scissors as a metaphor to make the game interaction easy for the users. Using hand gestures is the natural way of playing the traditional game, so using them in a digitized version of the game should facilitate the learning process and make it easier for the players to interact with the ghosts. Figure 18 illustrates the three different hand gestures that the game recognize. Each of these gestures should be displayed clearly in the front camera as shown in the figure exactly in order for the application to recognize them. This was mentioned explicitly to the second and third field trial round participants before they tried the application since the first trial round revealed that the participants did not know how to interact with the application without explaining them in detail how to perform the hand gestures. For instance some users were using the hand gestures properly, but their hands were out of the camera FoV, so it was impossible for the application to detect the hand gestures.

5.4.2. Buttons

The alternative way of interaction is using buttons. Having both the buttons and the hand gestures interaction methods in the same application will provide insights about interaction techniques in both smartphone and smart glasses. Each button was associated with a unique gesture. For smartphones, the buttons were virtually displayed on the screen and the players can tab them in order to use them. However, for the smart glasses, physical buttons were implemented since the users cannot interact with the virtual buttons without a physical device provided by the ODG called the speed mouse (Figure 19).

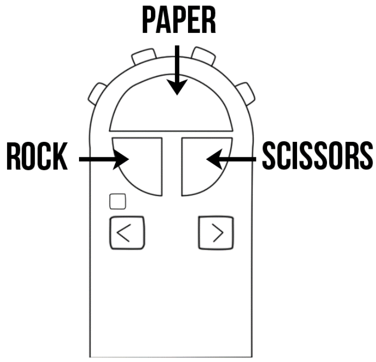


Figure 19. The ODG's Speed Mouse and the buttons used for Ghost Hunters.

The user simply clicks the button that corresponds to the gesture he/she wants to perform like "paper" for instance. So in order to play the game perfectly, the users must memorize the buttons functionalities which is assumed to be a difficult task in such short amount of time.

5.5. User interface

After discussing the interaction methods, now it is time to discuss the user interface (UI). The UI of both devices (smart glasses and smartphone) is quite similar, the main difference is in the interactive buttons method as mentioned earlier. While the smart glasses version have physical interactive buttons, the smart phone version have virtual interactive buttons that are embedded in the UI of the game (Figure 21).

For the smart glasses version, the UI was kept minimal in order to reduce the distraction that it might cause to the players. The UI mainly consists of text and images and no buttons since virtual buttons are hard to use in smart glasses. Figure 20 Illustrates the initial UI for the smart glasses version.

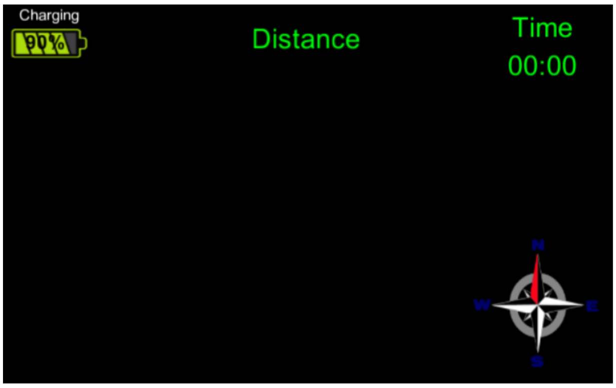


Figure 20. The initial UI layout for Ghost Hunters, this view only contains the UI elements and no distracting background.

The UI can be grouped into four sections based on the UI element location on the screen.

1. **Top Left:** a battery sign with 5 levels that shows the battery state of the "goggles". Above it, there is a small text that can be either "Charging or Discharging" that indicates whether the "goggles" is consuming or absorbing energy. Participants of the third field trial were asked whether they noticed this UI element or not, this would help identifying the different variables that affect the users perception of the UI especially in the smart glasses.

2. **Top Right:** A counter that displays the remaining time of the game. If the counter reaches 0 the player automatically loses the game.

3. **Top Center:** A simple text shows how far is the player from the nearby ghost.

4. **Bottom Right:** A compass is shown indicating the orientation of the player. The main reason for showing it is to make the user to know their orientation while working around the campus.

After running few tests, it was found that the GPS was not working properly indoors with the smart glasses, so it was decided to keep the game static and remove the "distance" from the UI. However the participants were not told about this in order to see how they would react. In addition to that, a "score" text was added later on right side of the screen to give the players a feedback about the how many ghosts they have captured. Also a simple device vibration was executed when the user captures a ghost to make the experience more immersive. Finally a simple text that says "Warning, Ghost nearby, focus on one area" was displayed before spawning the ghosts. The main reason for that is that the game fails to show the ghost sometimes when the user is moving the device while the game is spawning the ghost, and this is one of the limitations of the tracking SDK used. Even though the compass was not needed since the indoor positioning system did not work on the glasses, users did not complain about it and found it was a nice touch.

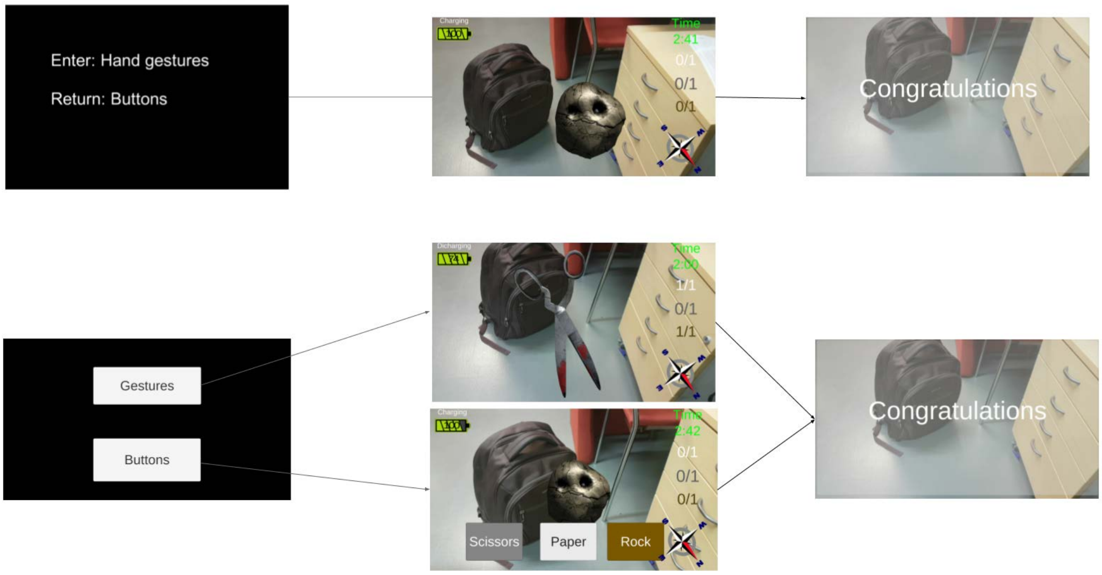


Figure 21. The UI flow for both smart glasses (top) and smartphone (bottom).

Figure 21 illustrates the UI flow of both devices. On the left, there is a selection menu in which the user can choose the preferred interaction method to capture the ghosts (either buttons or hand gestures). In the middle, the actual gameplay scene in which a camera feed is shown to the user along with a modified version of the UI shown in Figure 20. The ghosts appear in the middle of the screen making the UI visible for the user. As mentioned earlier, before showing the ghost, a simple text that says “Warning, Ghost nearby, focus on one area” appears to the player.

5.6. Ghost models

After the first field trial, it was found that the ghosts models should be changed based on the participants’ feedback. These changes could be seen in Figure 22.

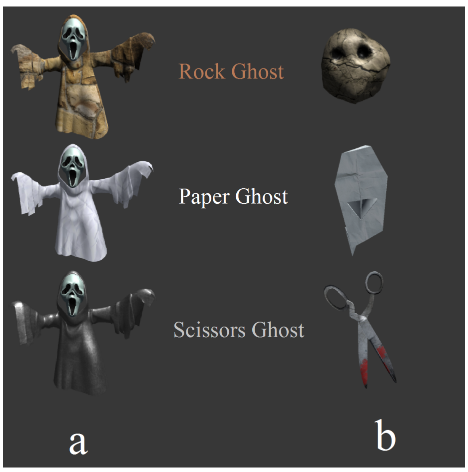


Figure 22. The ghosts models, (a) before and (b) after the first first field trial.

At first, there was only one ghost model with three different textures that represent which element or type the ghost belongs to. The ghost model (Figure 22 b) looks like a Grim Reaper which is a mythical creature that takes the souls of people when they are about to die. The Rock ghost had a brown texture that represents the sand or rocks, the Paper ghost had a white texture with some crimps, and finally the Scissors ghost had a black metallic texture with some scratches. As described later in section 6.1.1, some users could not distinguish between the ghosts and pointed that the models of the ghosts should be unique. For that, the ghost models were redesigned in order to make them look different.

5.7. Implementation

In this section the technical details of Ghost Hunters are described. The section is divided into two subsections where the first one describes the overall system architecture and the second one introduce the sub-systems and components in detail.

5.7.1. Overall system architecture

The overall system architecture consists of three major parts as shown in Figure 23. First there is the main script that uses data from handlers to drive the game logic. Second, there are handlers that interacts with resources and external SDKs and the the main script. Third, there are the compiled native SDKs, plugins, and libraries that provide external functionalities that Unity does not support by default.

The core of the game was made using Unity3D [69] which is a well-known 3D game engine used for commercial games. Unity is a cross-platform game engine, meaning it can be used to make games that run on different platforms (Windows, Linux, iOS, Android, PS4 etc.) with the same code. For the Android platform, the activity class is used to draw UI on the screen. By using Unity, the UnityPlayer activity becomes the main activity where all the UI is drawn.

The main script acts like a manager script that takes information from different handlers and use them to drive the game logic accordingly such as updating the UI element and determining when the players win or lose the game. It regularly reads data from the light sensor plugin handler to update the light data value and then update the battery icon and the text that indicates weather the in-game goggles are charging or discharging in the UI.

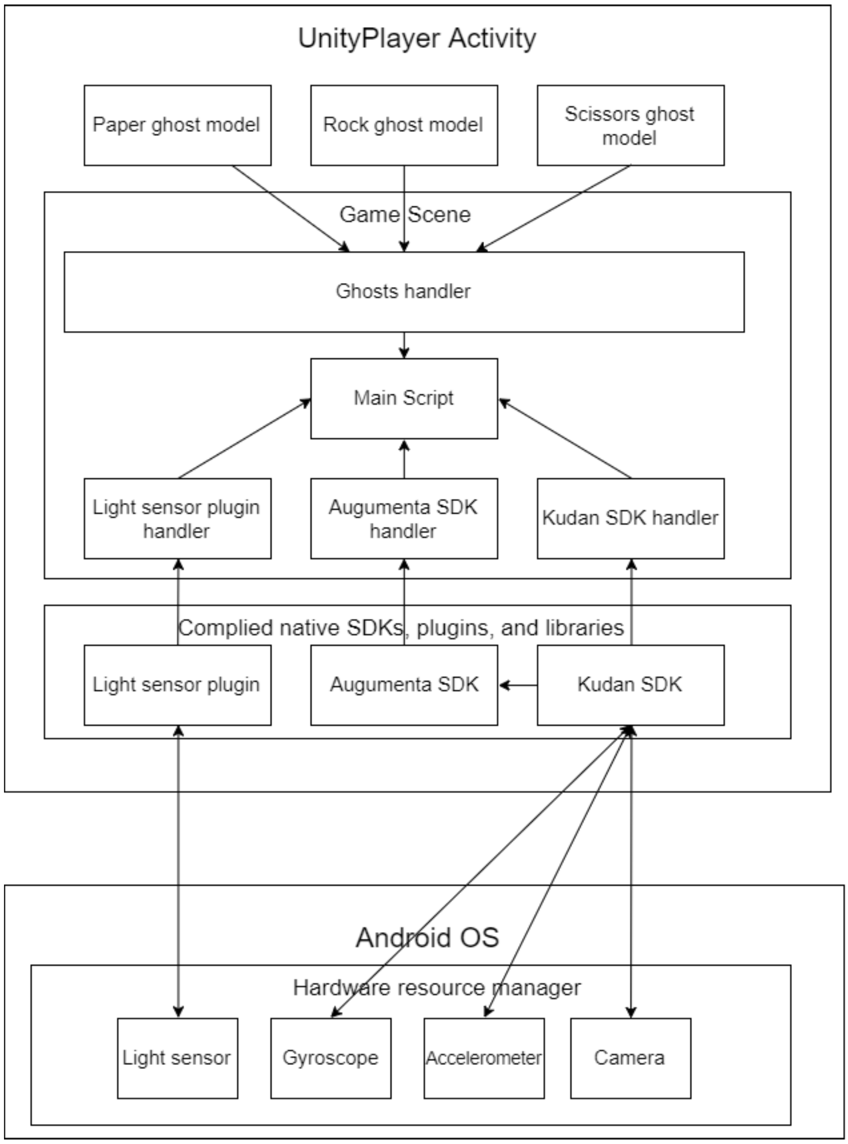


Figure 23. System architecture.

Data from Kudan SDK handler was used to keep track of the ghosts when spawned by the ghost handler that decides which ghost to spawn (render). Augumenta SDK was used to detect the user's hand gesture and determine whether it is the right gesture to capture the current ghost or not in order to update the score in the UI.

5.7.2. Sub-systems and components

By default, Unity does not support reading data from some of the smartphone sensors like the light sensor, so a native plugin had to be created in order to get such data. The plugin was made using Java and developed in Android Studio 2.1.2 Integrated Development Environment (IDE). It simply reads the values from the light sensor and then send them to the Main script through the Light sensor plugin handler. For the markerless AR, Kudan SDK [70] was used. The SDK is an image processing library that extracts features from the camera feed to keep track of the user position. Based on this information, the main script can render a 3D model in a certain area of the screen while keeping track of its position. No predefined images nor scanning of the area is needed, thus the SDK is perfect for scalability. For the hand gestures, Augumenta SDK [71] was used. Similar to Kudan SDK, Augumenta SDK uses image processing to detect the hand position on the screen and recognize which gesture or pose the user is doing. There was a problem of making Kudan and Augumenta SDKs working together since both of them try to access the camera at the same time. The easiest solution was to get the camera feed from Kudan SDK and then send it to the Augumenta SDK using a simple script, but since not all Unity textures are readable, meaning their pixels can not be read, the content of the camera feed had to be copied in a RenderTexture which is a texture that can be created and rendered in run time and then transfer its content to a custom readable texture and finally feed it to Augumenta SDK. This process of creating a dynamic RenderTexture and copying its content requires computational power and thus, made the game consume more energy than typical AR applications. Other solutions and attempts to optimize this process were tried but none of them worked.

6. EVALUATION

After discussing the design and implementation of Ghost Hunters, the evaluation process used to evaluate the prototype and answer the research questions is described. In the beginning, the two field trial rounds, their aim, and the participants involved along with their feedback are described. Afterwards the third field trial is discussed in detail where the setup, the participant recruitment and demographics, and data collected are described.

6.1. Evaluation process

The evaluation of Ghost Hunters was conducted in three field trials. The first pilot trial aimed at improving the game performance and usability. The second trial aimed at improving the study setup and questionnaire. The third and final trial aimed at answering the research questions.

6.1.1. First trial: the pilot

Before evaluating the interaction techniques in Ghost Hunters, a pilot evaluation was conducted to test the usability of the prototype in the smart glasses and get early feedback for the game. The gesture control of the game was evaluated during a two day event organized on at Oulu University campus for high school students who tried some VR and AR demos including Ghost Hunters. [3] In addition to that, a performance test was conducted to see how much the glasses consume energy compared to a decent tablet. The results show that Galaxy Nexus 9 consume less energy than the ODG's R7 glasses. However both devices can run the game for around 30 min [3]. The evaluation sessions were conducted in a space, full of illumination lights making it brighter than typical indoor spaces. This brightness affected the performance and accuracy of the hand gesture recognition (Argumenta SDK), so participants were taken to a less bright corner of the lab. 30 participants (12 female) of 17-19 years in age played one game session where they were supposed to capture three ghosts that were located in the same place thus the participants did not have to move around. Since the aim was to explore novice (untrained) use of gesture control with the smart glasses, the participants were not given a chance to practice gestures with it before the game session. All participants reported being familiar with the rock-paper-scissors game in advance. Questionnaires, field notes and in-game video data were gathered. The reason for that is to see how the participants interacted "natively" with the game, check if they could recognize the ghost types, and examine which hand gesture they used. The first pilot test showed that the game concept is interesting and most of the users gave a positive feedback about the user experience. However, few participants reported that they have the color blindness medical condition which made it hard for them to distinguish between the ghosts. This issue was solved by adjusting game graphics in a way that each ghost now has a unique model as shown in Figure 22.

6.1.2. Second trial: improving the study setup

After the first trial, the game was improved based on the feedback received from the users. In the second field trial, the aim was to compare usability on both smart glasses and the smartphones. For this field trial, four different conditions (Table 2) were used depending on the number of devices and methods of interaction. smart glasses hand gestures (SGH), smart glasses buttons (SGB), smartphone hand gesture (SPH), and smartphone buttons (SPB).

Table 2. The conditions used to evaluate the Ghost Hunters.

Condition	Device used	Interaction method
SGH	Smart glasses (ODG R7)	Hand gestures
SGB	Smart glasses (ODG R7)	Buttons
SPH	Smart phone	Hand gestures
SPB	Smart phone	Buttons

The participants were divided into 3 groups, group 1 tried all the four conditions, group 2 tried smart glasses conditions only, and group 3 tried the smartphone conditions only. The reason for having three different groups is to see which interaction method is better within one device, and then compared the two devices based on feedback from the group 1. 15 participants of 21-33 age from different backgrounds (business, computer science, mathematics, and tourism) evaluated the prototype after trying the game twice for group 2 and 3 (two different conditions within the same device), or four times for group 1 (tried all four conditions). The Computer System Usability Questionnaire (CSUQ) (Appendix 2) was used to collect quantitative data, one can notice that the questionnaire has 3 additional questions related the Ghost Hunters games, these questions are:

1. The game felt challenging.
2. The interaction with the system was natural/easy.
3. The ghosts were easily distinguishable.

Surprisingly, group 1 participants complained about the long duration of the evaluation which was a little bit more than 15 minutes on average. However, they gave more positive feedback than the other two groups in all the four conditions with the SPB condition having the best score. All participants complained about some ambiguous questions like 9 and 10 for instance that asked about error messages. Moreover, some participants said that if they had tried the hand gestures before, they would have given lower points for the button version. Overall, all the participants liked the game idea and found it interesting which is similar to the findings from the first field trial.

Finally, the questionnaire was modified to contain questions that can be used to evaluate both the usability and game engagement.

6.2. Third trial: the final evaluation

After two iterations, the final evaluation was conducted with an improved version of the game, a larger number of participants, and a more suitable questionnaire.

6.2.1. Evaluation setup

The third evaluation was conducted in a study place situated in the University of Oulu, Finland campus called TellUS. The main reason for choosing this particular place is to have diversity among the participants since students and staff members from all the faculties come there to study, relax, or have a meeting. The same four conditions used in the second trial were kept, but this time, each participant tried only one condition of the game (Figure 25) to avoid both the learning effect and confusing the user by giving feedback on two different devices which made some participants complain about giving one of the devices lower scores if they tried it first as mentioned earlier in 6.1.2. The researchers waited in the TellUS and asked the bypassers whether they would like to evaluate an AR game.

Figure 24. A researcher explains the game rules to a participant.

Researchers set in the main hall and asked people around them to try the game. Some people refused to participate because they were either preparing for exams or they were on their way to a meeting. The evaluation process had 5 steps :

1. After agreeing on participating, the user was asked to fill the background questionnaire (Appendix 1).

2. A researcher explained to the participant the purpose of the experiment and the basics of how to play the game. The explanation was kept the same for all conditions.

3. After playing the game, the user was asked to fill a questionnaire (Appendix 3).

4. A short interview with the participant was conducted and recorded.

5. A researcher gave a coffee voucher to the participant and thanked them for participating.

6.2.2. Participants

62 bypassers were asked to participate in the evaluation and 63% of them accepted to participate (Table 3). The 39 participants were from different backgrounds (computer science, mathematics, engineering, geology, and business).

Table 3. Participants data

Number of people asked	62
Accepted participating	63%
Male/Female ratio	M: 65% F: 35%
Mobile devices owned	Smartphone: 100% Tablet: 35%
Plays mobile games	45%
Main categories for played games	Action, Adventure, Racing, Puzzle, Card game
Prior AR experience	30%

Although the aim was to have an equal gender distribution, only 14 females (35%) agreed to participate, meaning the rest 25 participants (65%) were males. All participants own a smartphone, however only 14 participants (35%) own a tablet and 18 of them (45%) play regularly on their smartphone.

(a) A SGH participant.

(b) A SGB participant.

(c) A SPH participant.

(d) A SPB Participant.

Figure 25. Images from the final field trial that illustrate a user from each condition.

The games played differ between users. The main categories of the games played by the users are action, adventure, racing, puzzle, and card games. Only 30% of the participants (12) had used AR applications or devices before.

6.2.3. Data collected

The custom questionnaire used for the third field trial combines two famous standard questionnaires, the SUS questionnaire [1] which is a standard questionnaire for evaluating the usability of the system, and the Game Engagement Questionnaire (GEQ) proposed by Brockmyer et al. [2] which provides a psycho-metrically strong measure of levels of engagement, and finally three additional questions related to the Ghost Hunters prototype. Both questionnaires in addition to 3 custom questions, were merged together in such a way that the first 10 questions were from the SUS questionnaire, the following 18 questions were from GEQ, and finally the last 3 questions are the custom questions mentioned in 6.1.2. The final questionnaire can be found in Appendix 3. In addition to the questionnaire, a short recorded interview was conducted. The participants were asked about whether they noticed the battery sign in the UI (upper left corner in Figure 20), and if yes what do they think it represents. Moreover, the participants were asked about their opinion on using the surrounding light data in AR games. Finally, the participants were asked about the other interaction technique that they did not try, for instance if they tried hand gestures they would be asked about their opinion on using buttons in the same device instead of the hand gestures. Giving feedback on an interaction method that the user did not try can provide insights about what users think about the interaction methods in advance.

7. RESULTS

In this section, both the quantitative and qualitative results obtained in third and final field trial are presented. As mentioned earlier, the final questionnaire was a combination of two different questionnaire, SUS, and GEQ. Each of these two standard questionnaires will be analyzed separately.

7.1. System usability scale questionnaire

Since Finstad et al. [72] demonstrated that using a 5-point Likert scale questionnaire will result in user's interpolation of the answers, meaning they will try to give a non district answer, something like 3.5 for instance. However, a 7-point Likert scale questionnaire was shown to be a better solution where users did not have to interpolate. Hence, a 7-point Likert scale questionnaire was used. Thus, the formula that calculates the SUS score had to be reformulated since it was meant to be used with a 5-point Likert scale questionnaires.

To calculate the SUS score, one needs to subtract the minimum value of the Likert scale points from the odd questions (question 1,3,5,7,9) while subtracting the values of the even questions (2,4,6,8,10) from the maximum value of the Likert scale. The results are summed and then multiplied by a ratio to convert it to percentages as shown below:

$$SUSscore = Ratio * \sum_{n=1,3,5,7,9} (Q_n - min) + (MAX - Q_{n+1})$$

The ratio is added to achieve a 100 percentage, that way the system can be compared to other systems. To calculate the ratio, the maximum score a participant can score without any ratio needs to be calculated. This is done by assuming that all the odd questions have the maximum value (7 in this case) while the even questions have the minimum value (1 in this case). In this case, the maximum score a participant can score without multiplying by the ratio is 60, thus the ratio is 1.667.

Table 4. The SUS results.

Condition	Number of participants	SUS score
SGH	10	73.3
SGB	10	64.3
SPH	10	67.7
SPB	09	65.0

It can be seen in Table 4 that the hand gestures are more usable than the buttons, especially with smart glasses, a huge difference was noticed in the score (73.3 for the hand gestures and 64.3 for the buttons).

Figure 26 illustrates the meanings of the different SUS results. The score ranges between 0 and 100 with 100 being the perfect score (best imaginable system) and 0 the

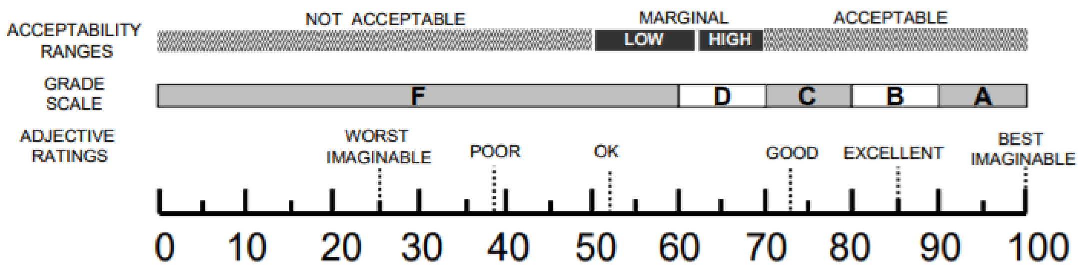


Figure 26. The SUS score [73].

worst imaginable system. All systems with a score lower than 50 are not acceptable. While systems between 50 and 60 are considered low marginal. Systems between 60 and 70 score are considered high marginal. Anything about 70 is considered acceptable. The hand gestures in smart glasses (SGH) was the only acceptable "Good" system, the rest were in the "OK" zone. Also, it can be noticed that SGH scored higher than SPH while SPB scored marginally higher than SGB and that was noticeable in the reaction of some participants who were amazed by the hand gesture version. From this, we can conclude that that hand gestures are better for smart glasses, however for smartphones, both hand gestures and buttons are usable with a slight advantage for hand gestures in such kind of AR games.

7.2. Game engagement questionnaire

For GEQ, the methodology presented by Brockmyer et al. [2] was used. The methodology consists of grouping the GEQ questions into four categories based on the psychological context of the question. These four categories are:

1. **Absorption:** is the term used to describe the total engagement in the present experience. In contrast to immersion and presence, and in common with flow, being in a state of psychological absorption induces an altered state of consciousness.

2. **Flow:** a term that describes the feelings of enjoyment that occur when a balance between skill and challenge is achieved in the process of performing an intrinsically rewarding activity.

3. **Presence:** As explained earlier, presence is the experience of being inside a virtual environment.

4. **Immersion:** immersion, as explained earlier is the game ability to make the gamer believe they are inside its world or environment.

To investigate how these elements were affected, the data was grouped based on different variables. Notice that we had 4 different conditions for the participants (SGH, SGB, SPH, and SPB) however the data grouping was different and can be found in Table 5.

Table 5. Grouping variables.

Grouping variable	Participants	Description
Device used	from all conditions	Data was grouped based on the device used (smart glasses group, and smart-phone group)
Interaction method	Either all conditions or from one device only	Data was grouped based on the interaction method of the participants (hand gesture group, and buttons group)
Prior AR experience	Either all conditions or from one device only	Data was grouped based on whether the participant had a prior AR experience (used AR software or hardware be-fore) or not.
Gamers/non-Gamers	Either all conditions or from one device only	Data was grouped based on whether the participant plays games on his/her phone or not.
Gender	Either all conditions or from one device only	Data was grouped based on the participant gender.
Age	Either all conditions or from one device only	Data was grouped based on the participant age range (younger than 25, between 25-30, older than 30)

In the upcoming sections, the results will be discussed in more detail. Each section provides insights about certain user groups. First, data from both devices is combined to compare the effect of the device and interaction method at the same time. After that the data from each device is examined separately.

7.2.1. All users combined

The mean rank of the each device (Table 6) indicates that there might be a correlation between the immersion and the device used.

Table 6. The mean rank of each device.

	Device	N	Mean rank
Noticing the battery UI	Glasses	20	18.23
	Smartphone	19	21.87
	Total	39	
Flow	Glasses	20	18.40
	Smartphone	19	21.68
	Total	39	
Presence	Glasses	20	20.75
	Smartphone	19	19.21
	Total	39	
Immersion	Glasses	20	23.85
	Smartphone	19	15.95
	Total	39	
Absorption	Glasses	20	20.53
	Smartphone	19	19.45
	Total	39	

The Kruskal-Wallis H analysis (Table 7) shows that indeed the used device has influenced the immersion of the users with smart glasses users being more immersed with a mean rank of 23.85 while the smartphones users had a mean rank of 15.95.

Table 7. Effect of device on the game engagement.

	Noticing the battery UI	Flow	Presence	Immersion	Absorption
Kruskal-Wallis H	1.440	.809	.179	4.878	.088
df	1	1	1	1	1
Asymp. Sig.	.230	.368	.672	.027	.767

Table 8. The mean rank of users according to their prior AR experience.

	AR experience	N	Mean rank
Noticing the battery UI	No prior AR experience	22	20.80
	Has prior AR experience	17	18.97
	Total	39	
Flow	No prior AR experience	22	20.75
	Has prior AR experience	17	19.03
	Total	39	
Presence	No prior AR experience	22	21.20
	Has prior AR experience	17	18.44
	Total	39	
Immersion	No prior AR experience	22	19.36
	Has prior AR experience	17	20.82
	Total	39	
Absorption	No prior AR experience	22	20.02
	Has prior AR experience	17	19.97
	Total	39	

It can be clearly seen in Table 8 and Table 9 that prior AR experience did not have any effect on neither the game engagement nor noticing the UI elements. This is probably because of the novel tracking method the Ghost Hunters prototype uses which is different from the tracking methods typically used in other AR applications.

Table 9. Effect of prior AR experience on game engagement.

	Noticing the battery UI	Absorption	Flow	Presence	Immersion
Kruskal-Wallis H	.356	.000	.219	.569	.164
df	1	1	1	1	1
Asymp. Sig.	.551	.989	.640	.451	.686

Table 10. The mean rank of users grouped by gender.

	Gender	N	Mean rank
Absorption	Male	25	20.18
	Female	14	19.68
	Total	39	
Flow	Male	25	20.98
	Female	14	18.25
	Total	39	
Presence	Male	25	18.92
	Female	14	21.93
	Total	39	
Immersion	Male	25	23.12
	Female	14	14.43
	Total	39	

Table 11. Effect of gender on the game engagement.

	Absorption	Flow	Presence	Immersion
Kruskal-Wallis H	.17	.515	.631	5.435
df	1	1	1	1
Asymp. Sig.	.895	.473	.427	.020

Even though prior gaming experience did not have a significant effect on the game engagement, males who were mostly gamers, were more immersed than females with a mean rank of 23.12 while females had only 14.43 (Table 10 and Table 11). This might be because males focused more on the gameplay and the game concept, while females were paying more attention to the device and its safety.

Surprisingly, the interaction method did not effect the game engagement in any case. Similarly to the interaction method, the age of the participants did not effect the game engagement at all. Finally, all the variables including, the device used, the interaction method, gender, and age did not effect noticing the battery UI element in the upper left corner (Figure 20).

7.2.2. Smart glasses users only

For the smart glasses, the prior AR experience had a small effect on the game engagement. The results show that participants with prior AR experience were more immersed (Table 12), this means they were more "drawn into the game" than users without any prior AR experience.

Table 12. The mean rank of smart glasses users grouped according to prior AR experience.

	Prior AR experience	N	Mean rank
Noticing battery UI	No prior AR experience	9	10.56
	Prior AR experience	11	10.45
	Total	20	
Absorption	No prior AR experience	9	11.22
	Prior AR experience	11	9.91
	Total	20	
Flow	No prior AR experience	9	12.78
	Prior AR experience	11	8.64
	Total	20	
Presence	No prior AR experience	9	12.67
	Prior AR experience	11	8.73
	Total	20	
Immersion	No prior AR experience	9	13.06
	Prior AR experience	11	8.41
	Total	20	

Table 13. The effect of prior AR experience on game engagement in smart glasses.

	Noticing battery UI	Absorption	Flow	Presence	Immersion
Chi-Square	.002	.246	2.435	2.25	3.246
df	1	1	1	1	1
Asymp. Sig.	.965	.620	.119	.136	.072

This effect might be due to the "wow effect" that most of the users had when using the glasses for the first time. All of them had tried Pokemon GO before and were impressed by the tracking system of the game which was better than the one implemented in Pokemon GO. It should be mentioned that the prior AR experience had a marginal effect on both flow and presence of the users which reflect how much they enjoyed playing the game while feeling inside its MR world. More data is required to provide insights about this effect.

Table 14. The mean rank of smart glasses users grouped according to the interaction method.

	Interaction method	N	Mean rank
Noticing the battery UI	Hand gestures	10	8.00
	Buttons	10	13.00
	Total	20	
Absorption	Hand gestures	10	8.45
	Buttons	10	12.55
	Total	20	
Flow	Hand gestures	10	9.40
	Buttons	10	11.60
	Total	20	
Presence	Hand gestures	10	9.65
	Buttons	10	11.35
	Total	20	
Immersion	Hand gestures	10	10.70
	Buttons	10	10.30
	Total	20	

Table 15. The effect of interaction method on game engagement.

	Noticing the battery UI	Absorption	Flow	Presence	Immersion
Chi-Square	4.798	2.421	.694	.419	.024
df	1	1	1	1	1
Asymp. Sig.	.028	.120	.405	.518	.876

Surprisingly, the interaction method affected the smart glasses users' perception of the UI. The users who used the buttons were more likely to notice the different elements in the UI, this might be because hand gestures are easy to use so the users were focusing more on the assigned task which is catching the ghosts in this case. Buttons were a bit tiresome, and many users complained that they had to remember the buttons layout (Figure 19). This might have forced them to check the UI in order to get hints or help them remember the buttons layout.

Both, the gender and age of participants did not have any effect on game engagement on smart glasses users.

7.2.3. Smartphones users only

For the smartphones, interaction method, gender, and age of participants did not influence neither the game engagement nor the perception of the UI elements.

7.3. Interview Results

25 of the participants (64%) noticed the battery sign in the UI (top right corner of the UI in Figure 20) from which only two participants mentioned that the battery was some sort of "health" of the player, the rest 23 thought that it represents the battery of the smart glasses (the real hardware battery). Therefore, it is not recommended to use familiar icons as a metaphors without explaining them explicitly to the users.

All the participants liked the idea of using the light data in such AR games. Some of them said: "It something I've never seen and I'm kinda experienced with games", "IT'S GREAT!!!", "That's cool!!!", "It's a clever idea!", "It's interesting!!!", "It's very cool" etc. This feedback reflects the acceptable SUS score the game had in all the conditions.

Some participants mentioned that the light data makes the game more engaging and immersing, while others said that it encourages people to move around the place making them to exercise. One participant said that "I automatically think over the negative perspective that there are people who forget about themselves and time, so I think this is a good thing for such kinda of talking" another participant added "It prompts movement and more interaction with the surroundings". However, few participants mentioned that even though the idea is nice, the game should balance between the darker and the lighter areas to make the game even more engaging.

When asked about the other interaction method that the user did not use. Interesting results were found. All the users who tried the smart glasses regardless of the interaction method they used, agreed that the hand gestures are more suitable for interaction. Moreover, the users that tried the buttons with the smart glasses complained about having to remember the buttons layout (buttons' functionalities). By using the hand gestures, the interaction becomes more natural and seamless, thus the system become more usable.

The male participants who used hand gestures with smartphones thought that the buttons would make the game unoriginal and it will break the whole aspect of the game. However, the females were more concerned about the smartphone safety and mentioned that buttons would make it easier and safer to use the application. This explains why males were more immersed since most of them paid more attention to the gameplay while the females were more concerned about the hardware safety.

Overall, some participants criticized the use of hand gestures with the smartphone version in the sense that it requires the user to hold the phone with one hand which is tiresome on the long run. However, using buttons (on the smartphone) requires users to read the text or interpret the icon making it less natural as some users reported.

With the smart glasses, users would have to memorize the buttons' functionalities but some users were just trying to press all buttons since they forgot what each button represents. However, hand gestures solve these issues since they are natural and are easy to remember if chosen appropriately.

8. DISCUSSION

After presenting the results, now it time to reflect on them to answer the research questions, expose the limitations of the work, and suggest some ways of extending it.

The findings of this thesis suggest that smart glasses are more immersive than the smart phones despite the interaction method used. This result goes well with Milgram et al. [74] findings in comparing different AR displays which suggest that the optical see-through HMD (OSTHMD) are more immersive than the monitor based displays.

The findings show that the answer for the first research question "Which interaction method is more suitable for smartphone and smart glasses?" is that the hand gestures are more suitable than the buttons in both devices since they are more natural and make the users more immersive. However the application designer should be aware that some smartphone users might not feel comfortable holding their devices with one hand while using the other to interact with the application for a long period of time. This explains why the hand gestures were marginally better than the buttons in smartphones in terms of usability. Hence, if the designers wants the users to be immersed in short experiences, they can confidently use hand gestures.

For the second research question which is about using environmental data in pervasive AR games, it was clear that all users liked the idea of using environment data in general and light data specifically in AR games. Thus the AR game designers are encouraged to include such data in their game mechanics. However, some users suggested balancing between the "advantages" of being in a dark or bright area, hence a game designer should design the game carefully so that the environment data being used in the game will not force the user to play in certain conditions every time. One simple solution for that is to associate some game events with every possible value of the environment data being used. For instance, low value of the light sensor triggers the event of spawning a giant monster or ghost, medium values charge the in-game goggles, high values show error message that indicates the in-game goggles are overheating and they would broke if the user stayed in that bright area for a certain amount of time. There was no significant difference between the immersion level of gamers and non-gamers, which is the opposite of Ho et al. [75] findings that suggest that the more experienced gamers are more immersed than compared to less experienced gamers. This could be due to the fact that the game idea was novel and pervasive which made the immersion in this case independent of the user's previous gaming experience. Gender affected the immersion of the users' with males being more immersed than females. The main reason for this is that males were more focused on the game-play and the overall game concept, while females were more concerned about the device safety.

With smart glasses, the interaction method seems to affect the way users perceive the UI. When using the buttons users paid more attention to the UI elements, hence noticing most of them. This is probably because the use of hand gestures steered users' focus more on doing the assigned task which was capturing the ghosts in this case.

The usage of smart glasses for indoor AR applications is highly recommended, especially for applications that use hand gestures. Such application could be maintenance applications where the application can for example show the places or items to be repaired and how to repair them.

8.1. Limitations

It was obvious in the trials that the tracking SDK (Kudan) failed to spawn ghosts few times on the smart glasses and that is due to the fast head movement of the players. However, no participant complained about it and despite that, the smart glasses conditions got higher SUS score than the smartphone conditions which did not suffer from such system failure. Moreover, only a single model of smart glasses were used, ODG R7, different smart glasses such as Microsoft HoloLens might have given different results since they can provide a different experience such as a different FoV for instance.

The game session lasted for about 2-3 minutes. If the game had lasted longer, the hand gestures might have affected both the usability and game engagement since it might make the users tired.

Even though GPS was working fine indoors for the smartphone version with an acceptable accuracy, it did not work well on the smart glasses due to physical constraints. This is because of the smart glasses' design which make shielding and tuning quite challenging when trying to minimize the weight [76]. For that, other indoor localization techniques such as Bluetooth beacons [77][78] is suggested. With such techniques, Bluetooh devices are scattered in a room, and based on the Bluetooth signal strength from each device, one can localize the desired device. However, this solution requires external hardware and a computational power to calculate the position of the device. Another alternative is to use a 3rd party indoor tracking solution such as IndoorAtlas which uses magnetic field of the building to locate the device [79]. IndoorAtlas requires the developer to scan the building first to generate a map of the building which can later be used to determine the position of the device. This means that applications that are made using such technology are hard to scale since scaling will require the developers to scan every single building that they want to use in their application. But for small targeted applications such as real estate maintenance where the building are already predefined, one can use such technologies. The same goes for the collaboration tasks where users are required to work together on a virtual content such as 3D model of a building. Hands-free applications will allow the users to focus more on the assigned task in a more immersive and maybe even more productive way.

8.2. Future work

The work done in this thesis can be extended by :

1. Other OST-HMDs can be used to compare their usability and effect on game engagement as well.
2. The game session should be extended to collect more data.
3. Speech input can also be added to compare it with the other two interaction methods.
4. Since the gaming did not affect the game engagement with smartphones, one can create a similar AR application which does not have to be a game, do the same evaluation as the one done with Ghost Hunters, and then compares the results.

5. More investigation is needed on the gender effect on AR applications.
6. The UI on the smart glasses is still ambiguous and requires further investigation, one can add more UI elements and then ask the participants to describe the UI as they remember it.
7. Adding extra localization techniques such as IndoorAtlas and then run another field trial where users play for a longer period of time since they would have to visit many physical locations.

9. CONCLUSION

In this thesis, a pervasive AR game, Ghost Hunters, was presented. The thesis explores the use of environmental data and two different interaction techniques natural hand gestures and buttons with both smart glasses and smartphones, in mobile pervasive AR games. The first research question presented in this thesis is "Which interaction method is more suitable for smartphones and smart glasses". The second research question addressed is whether the use of environmental data in mobile pervasive AR games is beneficial or not.

Ghost Hunters, the prototype created to investigate the research problems, was developed using Unity3D, Kudan SDK, and Augumenta SDK. The prototype was evaluated in three rounds of field trials with 84 participants in total. The first trial showed that the game is engaging and fun. However, the graphics of the game were confusing for some of the participants. The second trial helped improving the evaluation setup and the used questionnaires. Finally, the third field trial provided answers to the two research questions.

The findings suggest that even though the application failed to detect hand gestures few times, the hand gestures are still more usable than the buttons in system usability scale. However, the score difference in the smart glasses version was significant in opposite to smartphones version where it was lower.

The smart glasses were found to be more immersive than smartphones in AR applications. Similarly, males were more immersed in the game than females with both devices and this might be due to the fact that males focused more on the gameplay and the idea of the game than females. Prior AR experience had a marginally significant effect on the immersion of smart glasses users. This is because the users who have earlier tried other AR applications mostly used a smartphone and were probably impressed by the tracking of the virtual content in the smart glasses even though the tracking was independent from the smart glasses.

The interaction method affected the players perception of the UI in the smart glasses. Users who used the buttons were more likely to notice the UI elements than the users who used the hand gestures and that is because the latter group of users was more immersed and focused on the assigned task instead of what is displayed in the UI.

For the future work, multiple headsets and hand-held devices are needed to collect more data that can be used to provide insight about other interaction techniques along with the hand gestures and buttons. In addition to that, adding more environmental data and scaling the prototype to be played both indoors and outdoors will give some hints on which data is more suitable for each location. Finally, more investigation needs to be done on the UI of the smart glasses since it was clear that the interaction method played a significant role in noticing some elements.

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11. APPENDICES

Appendix 1. Background questionnaire

Appendix 2. CUSQ

Appendix 3. SUS + GEQ Questionnaire

Appendix 1. Background questionnaire

Background questionnaire ID: ......

Your age: .... Gender: [] Female [] Male [] other

Your Current profession.........

If student, your Field of study:.........

Technical devices: Do you have a touch screen smartphone?: [] Yes [] No Manufacturer:..... Model:....

Do you own a tablet device?: [] Yes [] No Manufacturer:........... Model:......

Do you have previous experience on augmented reality applications or devices? [] Yes [] No

If you answered yes, what kind of applications and/or devices you have used? ....

Appendix 2. CUSQ

		1	2	3	4	5	6	7	
1. Overall, I am satisfied with how easy it is to use this system	strongly agree								strongly disagree
2. It was simple to use this system	strongly agree								strongly disagree
3. I can effectively complete my work using this system	strongly agree								strongly disagree
4. I am able to complete my work quickly using this system	strongly agree								strongly disagree
5. I am able to efficiently complete my work using this system	strongly agree								strongly disagree
6. I feel comfortable using this system	strongly agree								strongly disagree
7. It was easy to learn to use this system	strongly agree								strongly disagree
8. I believe I became productive quickly using this system	strongly agree								strongly disagree
9. The system gives error messages that clearly tell me how to fix problems	strongly agree								strongly disagree
10. Whenever I make a mistake using the system, I recover easily and quickly	strongly agree								strongly disagree
11. The information (such as online help, on-screen messages, and other documentation) provided with this system is clear	strongly agree								strongly disagree
12. It is easy to find the information I needed	strongly agree								strongly disagree
13. The information provided for the system is easy to understand	strongly agree								strongly disagree
14. The information is effective in helping me complete the tasks and scenarios	strongly agree								strongly disagree
15. The information is effective in helping me complete the tasks and scenarios	strongly agree								strongly disagree
16. The interface of this system is pleasant	strongly agree								strongly disagree

17. I like using the interface of this system	strongly agree								strongly disagree
18. This system has all the functions and capabilities I expect it to have	strongly agree								strongly disagree
19. Overall, I am satisfied with this system	strongly agree								strongly disagree
20. The game felt challenging	strongly agree								strongly disagree
21. The interaction with the system was natural/easy	strongly agree								strongly disagree
22. The ghosts were easily distinguishable	strongly agree								strongly disagree

Appendix 3. SUS + GEQ Questionnaire

Please, encircle which of the items on the scale corresponds to your opinion.

	strongly agree						strongly dis-agree
1. I think that I would like to use this system frequently	1	2	3	4	5	6	7
2. I found the system unnecessarily complex	1	2	3	4	5	6	7
3. I thought the system was easy to use.	1	2	3	4	5	6	7
4. I am able to complete my work quickly using this system	1	2	3	4	5	6	7
5. I found the various functions in this system were well integrated.	1	2	3	4	5	6	7
6. I thought there was too much inconsistency in this system.	1	2	3	4	5	6	7
7. I would imagine that most people would learn to use this system very quickly.	1	2	3	4	5	6	7
8. I found the system very awkward to use.	1	2	3	4	5	6	7
9. I felt very confident using the system.	1	2	3	4	5	6	7
10. I needed to learn a lot of things before I could get going with this system.	1	2	3	4	5	6	7
11. I lost track of time	1	2	3	4	5	6	7
12. Things seemed to happen automatically	1	2	3	4	5	6	7
13. I felt different	1	2	3	4	5	6	7
14. I felt scared	1	2	3	4	5	6	7
15. The game felt real	1	2	3	4	5	6	7
16. If someone talked to me I didn't hear them	1	2	3	4	5	6	7
17. I got wound up	1	2	3	4	5	6	7
18. Time seemed to kind of stand still or stop	1	2	3	4	5	6	7
19. I felt spaced out	1	2	3	4	5	6	7
20. I didn't answer when someone talked to me	1	2	3	4	5	6	7

21. I couldn’t tell that I’m getting tired	1	2	3	4	5	6	7
22. Playing seems automatic	1	2	3	4	5	6	7
23. My thoughts went fast	1	2	3	4	5	6	7
24. I lost track of where I was	1	2	3	4	5	6	7
25. I played without thinking about how to play	1	2	3	4	5	6	7
26. Playing made me feel calm	1	2	3	4	5	6	7
27. I played longer that I meant to	1	2	3	4	5	6	7
28. I really got into the game	1	2	3	4	5	6	7
29. I felt like I just cant stop playing	1	2	3	4	5	6	7
30. The interaction with the system felt natural	1	2	3	4	5	6	7
31. The ghosts were easily distinguishable	1	2	3	4	5	6	7